Managing Invention and Innovation: From Delegated R&D to Implementation

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Abstract

In a two-stage framework, a manager delegates invention and makes innovation decisions after observing the quality of the invention. The optimal contract for delegated R&D is shown to take the form of an option. The analysis extends the principal-agent model to allow the principal to implement the invention ex post. The analysis further extends the principal-agent model to consider experimental design with simultaneous sampling and sequential sampling. The discussion introduces a general "implementation principle" that simplifies the analysis of moral hazard models and eliminates the need for monotonicity assumptions either on the contract or on the principal's benefit function. The model extends to various important statistical decisions: when the agent designs the experiment by choosing the distribution from which to sample, when the principal imperfectly observes the outcome of R&D,and when the number of samples is random.
KEYWORDS: R&D, Invention, innovation, contract, principal, agent, incentives (JEL Codes: D82, D83, O3).

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1 Introduction

Managers face major challenges in organizing invention and innovation. Research and Development (R&D) is a critical driver of the growth of firms and the growth of the economy.[1] R&D expenditures are substantial; total US private, nonprofit and government investment in R&D exceeds $400 billion per year with private R&D constituting over 10 percent of private fixed investment.[2] Companies manage these extensive R&D activities and manage the application of technological capital generated by R&D discoveries either through own-use of the technology or sale and licensing of the technology to other companies. Companies apply inventions by investing in innovative products, production processes, and transaction methods. Companies such as Apple, Boeing, Cisco Systems, General Motors, IBM, Intel, Johnson & Johnson, Merck, Microsoft, and Pfizer extensively invest in both invention and innovation.[3] Many leading companies say that "coming up with new ideas is not as big a problem as selecting and converting them to development projects" (Jaruzelski et al., 2012).

To address the interactions between invention and innovation, this study introduces a comprehensive framework that integrates the management of invention – before R&D takes place – and management of innovation – after R&D takes place. The analysis shows the critical interaction between the *ex ante* design of contracts to manage invention and *ex post* management of innovation that implements inventions. In practice, managers must motivate researchers on the basis of market performance of innovation. It is therefore necessary to integrate the manager's contract design decisions with innovation decisions. The key practical result of the analysis is that option contracts are optimal for managing the combination of invention and innovation.

Managers must design and apply incentive contracts for specialized economic agents who conduct R&D because most R&D is a *delegated* activity.[4] The skills, knowledge

[1] See Lee and Schmidt (2010) on the contribution of R&D to economic growth.

[2] See Lee and Schmidt (2010). The National Income and product accounts have switched from treating public and private R&D as current expenditures to treating them as capital investments (Bureau of Economic Analysis, 2013).

[3] The largest 1,000 global innovators spent over $600 billion on R&D in 2011 (Jaruzelski et al., 2012).

[4] National and international agencies view R&D as a delegated economic function. The United Nations Statistical Commission (2009, p. 119) in its System of National Accounts (SNA) defines R&D as "creative work undertaken on a systematic basis to increase the stock of knowledge, and use this stock of knowledge for the purpose of discovering or developing new products, including improved versions or qualities of existing products, or discovering or developing new or more efficient processes

and personnel necessary for the invention often differ from other production and operating activities and generally require independent business units.[5] Companies and government agencies conduct R&D in-house by employing specialized experts such as scientists, engineers, and statisticians. Companies and government agencies also outsource R&D by contracting with research laboratories, specialized firms, universities, and independent researchers. Firms contract with "star scientists" to increase organizational capabilities in scientific research (Lacetera et al., 2004) and to apply their discoveries (Zucker et al., 2002). Corporations and venture capitalists also engage in delegation of R&D through financing of entrepreneurial technology startups, specialized research firms and independent researchers. The challenge for managers is to provide incentives for specialized personnel to conduct R&D efficiently.

After researchers create inventions, managers organize innovation to implement inventions by own-use of discoveries within the company and commercializing intellectual property (IP). The firm's costs of innovation are distinct from R&D costs and involve expenditures devoted to managing and applying new technologies. After observing the outcomes of R&D, managers must decide whether or not to introduce inventions to the market and how much to invest in implementing inventions. Managers compare the returns and investment costs that are associated with alternative applications of inventions and different market channels for distributing disembodied IP (licensing, cross-licensing, IP sales) and embodied IP (products, services, production processes, transaction methods, spinoffs). Managerial innovation decisions affect the payoffs of R&D contracts to researchers and thus innovation decisions play a critical role in delegated R&D. The analysis shows that it is necessary to understand the linkages between contracts for delegated invention and innovation decisions.

The present analysis differs from standard models of R&D agency and from standard

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of production." According to the the United Nations Statistical Commission (2009, p. 119) "The research and development undertaken by market producers on their own behalf should, in principle, be valued on the basis of the estimated basic prices that would be paid if the research were subcontracted commercially, but in practice is likely to have to be valued on the basis of the total production costs including the costs of fixed assets used in production."

[5]Because R&D is delegated, managers cannot assume that reseachers will pursue efficient decisions without additional incentives for performance. Companies and sponsors of R&D must delegate decision-making authority to specialized researchers because it is costly for managers to monitor researchers' efforts and activities. Due to the specialized nature of R&D, managers generally lack the expertise to understand the design of experiments or scientific and technical efforts. R&D inputs may not be observable or verifiable by third parties so that it may not be possible or desirable to contract on investment in R&D activities.

models of technology management by considering the interaction between these two types of activities. Managers commit to incentive contracts for delegated R&D so that R&D agents within or outside the company choose inventive efforts given the R&D contract. However, we do not require managers to commit to implementation of inventions so that managers have the flexibility to make innovation decisions after observing inventions. By making innovation decisions ex post, managers benefit from the additional information gained by observing the outcome of R&D. We allow the manager and the researcher to renegotiate their contract after the agent reveals the invention but before the manager makes innovation decisions.

We introduce and derive an "implementation principle" that provides a useful way to model invention and innovation decisions. The "implementation principle" is a general technical contribution that should apply to any moral hazard model containing both incentives for delegated activities by agents and implementation decisions made by the principal. Using the "implementation principle," we extend the basic agency model to allow delegation of experimentation and statistical reporting to an agent and implementation decisions by the principal.

The integrated framework for studying invention and innovation generates a number of important results. First, we derive the "implementation principle" and we show that in equilibrium, the principal makes an optimal innovation choice on the basis of the realization of the invention. Also in equilibrium, the principal honors the contract offer initially made to the agent. The innovative outcome then is increasing in the quality of the invention because the innovation is increasing in both the quality of the invention and the implementation decision and because the implementation decision itself is increasing in the quality of the invention. The implementation principle implies that the payment to the agent also must be increasing in the quality of the discovery.

This result represents a general technical contribution to the agency literature with moral hazard, risk neutrality, and limited liability. Ex post implementation decisions by the principal allow us to eliminate two standard "monotonicity" assumptions: that the principal's utility is non-decreasing and that the contract is non-decreasing in the outcome. Elsewhere, we have shown that we can replace the commonly-used Monotone Likelihood Ratio Property (MLRP) with the much less restrictive Decreasing Hazard Rate in Effort Property (DHREP) (Poblete and Spulber, 2012). The "implementation principle" obtained here allows us to strengthen further the basic agency framework by also dispensing with monotonicity requirements.

Second, we apply the integrated invention and innovation framework to R&D in which there is *simultaneous sampling* from a probability distribution. We show that the optimal incentive contract for R&D takes the form of an *option*, which can readily be applied by companies in both internal contracts and outsourcing contracts. We further show that researchers shirk by taking *too few* observations when faced with option contracts. The researcher chooses the number of experiments or equivalently, the number of independent random draws from the distribution of potential results. The discovery that results from R&D is the highest value of the sample. By the theory of order statistics, this generates a probability distribution over realizations of the best outcome. The option contract is optimal because it is efficient to motivate the researcher by targeting the best outcomes as rewards for performance. The contract shifts all rewards to the agent when the quality of the invention exceeds a threshold and provides no rewards below that threshold.

Third, we show that with *sequential sampling*, the optimal incentive contract induces the agent to choose a stopping rule. It is well known that optimal sequential search involves a stopping rule but it is useful to confirm that optimal contracts induce this stopping rule when R&D is delegated.[6] We further show that the optimal incentive contract for sequential R&D takes the form of an option, so that option contracts are optimal under different types of experimental designs. However, in contrast to R&D with simultaneous sampling, the researcher deviates from the efficient outcome by taking *too many* observations. We show that with delegated R&D, the agent engaged in costly sequential search chooses an optimal stopping rule that based on the rewards for the quality of R&D. The agent sets a stopping rule that exceeds the optimum without delegation and thus engages in too much search.

Fourth, we address several important aspects of agency costs in *experimental design*. We show that the optimal contract is an option when the principal cannot perfectly observe the agent's report of the outcome of the experiment. We also show that the optimal contract is an option when the researcher chooses among distributions from which to sample by choosing the scale of the distribution. Finally, we give conditions under which the optimal contract is an option when the researcher's effort affects the distribution of the number of random observations and the researcher reports the sum of observations. The practical implication of our analysis is that delegated R&D departs from optimal statistical decisions considered in statistics, econometrics, engineering,

[6]See for example DeGroot (1970).

and various sciences.[7]

Using the "implementation principle," the outcome of innovation is contractible. Our analysis differs from studies in which the outcome of R&D is not based on implementation of inventions; see for example Holmstrom (1989) and Lazear (1997). Our analysis also differs from agency models in which a multi-tasking agent engages in both invention and innovation. Hellman and Thiele (2011) consider the effect of contract design in an agency model in which the agent can devote effort both to a standard task and an innovative opportunity, but chooses to devote effort to only one activity depending on the quality of the opportunity. Manso (2011) considers a two-armed bandit model of an agent who chooses between exploration and exploitation of a research project depending on the types of rewards for these activities. Azoulay et al. (2011) find support for Manso's (2011) analysis in their study of biomedical research and suggest that the design of incentives in research contracts and grants can affect the development of "breakthrough ideas" such as gene targeting. In an experimental setting, Ederer and Manso (2013) show that rewarding long term success without penalizing early failures is optimal in a dynamic setting where in each period an agent chooses between exploration of an unknown technology and exploitation of a known technology. Our model is related to Lewis (2011) who considers delegation of sequential search to an agent who devotes effort to increasing the likelihood of making an observation in each period, rather than the number of observations as in our framework. Lewis (2011) finds that with moral hazard the optimal contract gives the principal an option to purchase the invention.

Our analysis may be useful in understanding incentive contracts associated with transfers of intellectual property (IP). Such IP transactions are subject to problems of asymmetric information including moral hazard (Arrow, 1962, Zeckhauser, 1996, Spulber, 2008, 2010). Macho-Stadler et al. (1996) present a moral hazard model of technology transfer in which the inventor decides whether or not to transfer additional complementary know-how, although the level of know-how is given. The recipient of IP transfers often must compensate the inventor for the R&D outcome so as to provide incentives for knowledge transfers (Lowe, 2006, Olsen, 1993). Jensen and Thursby (2001) present a principal-agent model of invention with moral hazard in which the licensee's probability of commercial success depends on the inventor's effort. IP transfers including patent assignments and licensing can require additional effort by the inventor to

[7] For a comprehensive overview of optimal statistical decisions, see DeGroot (1970)

transfer tacit knowledge (Spulber, 2012).

Our analysis differs from studies that focus on relationship-specific investment and contract renegotiation in R&D.[8] Aghion and Tirole (1994) examine how the allocation of property rights within the firm affects investment incentives in R&D, and observe that shop rights, which are property rights contingent on the nature of the innovation, and rules governing breakaway research are ways of sharing ownership of the innovation. Nöldeke and Schmidt (1998) consider R&D joint ventures with relationship-specific investments and find that first-best investments can be achieved when one party owns the firm initially and the other party has an option to buy the firm at a set price. Options to buy the firm are robust to renegotiation and uncertainty. Nöldeke and Schmidt (1998) point out that contingent ownership structures such as warrants and convertible securities are often used in joint ventures. Lerner and Malmendier (2010) develop and test a theoretical model of a partnership between corporation that finances R&D and a specialized research firm in which the researcher can choose between narrow and broad research projects and the financing firm has the option to terminate the agreement. They find that the financing firm's option to terminate induces biotechnology research firms not to deviate from proposed research activities.

2 The basic model of invention and innovation

This section introduces a two-stage model of invention and innovation. First, the manager delegates R&D to a specialized agent who produces an *invention*. Second, after observing the quality of the invention, the principal introduces an *innovation* to the market by implementing the invention. The model differs from standard agency models in which only the agent takes an action. The model differs from standard optimal statistical decision making in which the statistician both conducts the experiment and chooses an action.[9]

[8] Merges (1999) and Burk (2004) consider investment incentives pertaining to allocation of ownership of inventions between employees and the firm. Merges (1999) also considers agency issues.

[9] The statistician can choose an action that maximizes a benefit function or minimizes a loss function (Blackwell, 1951, 1953).

2.1 The Agent

The agent is a researcher such as a statistician, engineer, scientist, social scientist, or inventor. The agent may be an employee of the principal or an independent contractor. The agent is risk neutral and has limited liability, which is normalized to zero. The agent has an opportunity cost $u_0 > 0$.

The agent chooses an *experimental design* that generates multiple realizations of a random variable.[10] If R&D consists of simultaneous sampling, then the agent's experimental design is the choice of the number of observations n of a random variable. If R&D consists of sequential sampling, we show that the agent's experimental design is a stopping rule that determines the expected number of observations of a random variable.[11]

The experimental design is the agent's effort or private investment. The agent incurs a cost c for each observation, so that the agent's total effort costs cn depend on the sample size. There is a moral hazard problem because the agent's R&D effort or investment is costly and because the principal cannot observe the agent's experimental design. The agent may shirk by choosing too little or too much effort as compared to the optimal effort level. Too little effort reduces the agent's R&D costs and but also reduces the expected quality of the invention. Too much effort improves the expected quality of the invention but increases the agent's R&D costs. With sequential sampling, too little effort speeds up invention and too much effort delays invention.

Next, the agent observes *experimental data* consisting of n independent and identically distributed random variables $X = (X_1, X_2, ..., X_n)$ with realizations $x_1, x_2, ..., x_n$. The experimental data are draws from a general probability distribution $F(x)$ that is common knowledge for the agent and the principal. Our main results hold for any probability distribution. The principal cannot observe the experimental data.

After completing R&D and observing experimental data, the agent reports the maximum order statistic to the principal,

$$t(X) = \max\{x_1, x_2, ..., x_n\}. \quad (1)$$

The realization of the maximum order statistic $t(X)$ is the *quality of the invention*. The quality of the invention depends on the agent's effort or investment. The statistic is

[10] See Blackwell (1951, 1953) on the general definition of an experiment. Adcock (1997) surveys the problem of sample size determination as a means of estimating unknown values of a parameter of a distribution function for both frequentist and Bayesian approaches.

[11] On search theory applied to R&D, see for example Weitzman (1979) and Spulber (1980).

a signal to the principal that describes the realizations of the random variable. The value of the statistic that the agent communicates to the principal is observable but *non-verifiable* by the principal.

The distribution of the maximum statistic t for a given sample size n is $H(t,n) = F^n(t)$ and the density equals $h(t,n) = nF^{n-1}(t)f(t)$. Although the sample size n is an integer, the function $H(t,n)$ is well defined, decreasing, and differentiable for any positive real value n. Define the hazard rate of the sufficient statistic for a given number of observations,

$$r(t,n) = \frac{h(t,n)}{1-H(t,n)} = \frac{nF^{n-1}(t)f(t)}{1-F^n(t)}. \tag{2}$$

We now show that the hazard rate satisfies DHREP *for any distribution* F. This property is useful for characterizing the form of principal-agent contracts (Poblete and Spulber, 2012). The reduced-form distribution $H(t,n)$ is said to satisfy DHREP when its hazard rate for $t < 1$ is decreasing in the number of observations n,$r_n(t,n) < 0$. To verify that DHREP holds, observe that

$$r_n(t,n) = F^{n-1}(t)f(t)\frac{1-F^n(t)+n\ln F(t)}{(1-F^n(t))^2} < 0. \tag{3}$$

The numerator is negative for $n \geq 1$. Therefore, the hazard rate of the reduced-form distribution satisfies DHREP.

To provide economic intuition for DHREP, consider the rate of return from incentives for delegated R&D. This is given by the *critical ratio*[12]

$$\gamma(t,n) = -\frac{H_n(t,n)}{1-H(t,n)}. \tag{4}$$

The benefit of increasing the slope of the payment to the agent at some t, is $-H_n(t,n)$. The cost of increasing the payment to agent at some t is $1 - H(t,n)$ if $\gamma_t(t,n) > 0$ because higher output levels are more efficient to induce the agent to increase the sampling effort. It can be shown that DHREP is equivalent to a rate of return $\gamma(t,n)$ that is increasing in the statistic t.

DHREP is a weaker requirement than the monotone likelihood ratio property (MLRP), which is said to hold when $\frac{\partial}{\partial t}\frac{h_n(t,n)}{h(t,n)} > 0$. MLRP is widely used in agency models.[13]

[12] Poblete and Spulber (2012) introduce this "critical ratio."

[13] This is because the likelihood ratio order is sufficient but not necessary for the hazard rate order (Shaked and Shanthikumar, 2007).

Although DHREP is sufficient for our results, note that the reduced form distribution $H(t, n)$ also satisfies MLRP.[14] The hazard rate order is a sufficient but not necessary condition for the reduced-form distribution to satisfy first-order stochastic dominance (FOSD) (Shaked and Shanthikumar, 2007). This can be readily verified in our setting, $H_n(t, n) = F^n(t) \ln F(t) < 0$.

2.2 The Principal

The principal is risk neutral and manages a firm that implements the agent's invention. Implementing the invention provides a benefit to the principal's firm such as a new product design, a new production process, or a new transaction method. The principal introduces an *innovation* to the market by taking an action z that implements the invention, t. The principal's implementation decision z can represent prices, outputs, product development, marketing and sales efforts, or capital investment in plant and equipment. The value of the innovation to the principal depends on the invention and its implementation,

$$\pi = \pi(t, z). \tag{7}$$

The value of the innovation π represents the principal's return from applying the invention and introducing the innovation net of the costs of implementation, excluding the payment to the agent for R&D. This framework is sufficiently general that it can handle many applied models of innovation management.

The following assumptions are useful for characterizing the principal's equilibrium implementation decision. We assume that invention and implementation are complements in innovation. For ease of presentation, we assume that there is a best implementation decision for each invention.

Assumption 1. *The value of the innovation to the principal $\pi(t, z)$ is continuously differentiable and strictly supermodular in (t, z), $\frac{\partial \pi(t,z)}{\partial t \partial z} > 0$.*

[14] The likelihood ratio equals

$$\frac{h_n(t, n)}{h(t, n)} = \frac{F^{n-1}(t))f(t)[1 + n \ln F(t)]}{nF^{n-1}(t)f(t)} = \frac{1}{n} + \ln F(t). \tag{5}$$

The effect of the outcome on the likelihood ratio is simply

$$\frac{\partial}{\partial t} \frac{h_n(t, n)}{h(t, n)} = \frac{f(t)}{F(t)}. \tag{6}$$

Assumption 2. *There exists a unique finite efficient implementation decision $z^0(t) > 0$ that maximizes $\pi(t, z)$ for every t.*

By monotone comparative statics (Topkis, 1998), these two assumptions imply that the efficient implementation decision $z^0(t)$ is strictly increasing in t.

The contract between the principal and the agent is fully described by a payment from the principal to the agent, w. The contract is based only on the outcome of innovation, π,

$$w = w(\pi). \tag{8}$$

The contract needs to provide incentives both for the agent to invent and for the principal to implement the invention. Because the agent has limited liability, the payment to the agent must be nonnegative, $w \geq 0$. The agent's limited liability rules out the principal selling the task to the agent and thus achieving an optimal experimental design. For ease of presentation, we restrict attention to contracts with $w(0) = 0$. This restriction is without loss of optimality of the contract.

For any innovative outcome π, the principal's net benefit is equal to the outcome minus the payment to the agent,

$$v(w, \pi) = \pi - w(\pi). \tag{9}$$

The agent's net benefit is given by the payment net of the cost of conducting R&D and the net of the agent's opportunity cost,

$$u(w, \pi) = w(\pi) - cn - u_0. \tag{10}$$

After observing the agent's report of the statistic, t, the principal chooses an implementation level z to maximize net benefits. The implementation level is assumed not to be contractible, and therefore the equilibrium implementation level must be incentive compatible according to the following definition.

Definition 1 *An implementation $z^*(t)$ is said to be incentive compatible for the principal at t under contract $w(\cdot)$ if*

$$z^*(t) \in \arg\max_z \pi(t, z) - w(\pi(t, z))$$

The agent anticipates the effect of the realization of the statistic on the principal's implementation decision $z^*(t)$.

The timing of the innovation game is as follows. Initially, the principal offers a contract $w(\pi)$ to the agent. Next, the agent conducts R&D by choosing a sample of size n and observing a sample X, proceding either simultaneously or sequentially. After that, the agent makes a non-verifiable disclosure to the principal of the statistic $t(X) = \max\{x_1, x_2, ..., x_n\}$. Then. the principal observes t and chooses an implementation level z. Finally, the principal and agent observe the innovative outcome $\pi = \pi(t, z(t))$ and the principal makes a payment $w(\pi)$ to the agent.

2.3 The Implementation Principle

This section introduces the "implementation principle," which is a highly useful method of characterizing the R&D outcome function. This is useful for our more general agency framework that addresses invention by the agent and innovation by the principal. The principal and the agent contract with symmetric but unverifiable information about the invention. The principal and the agent can renegotiate the contract after the agent reveals the invention but before the principal implements the invention. This assumption is a natural one because the invention is observable by both the agent and the principal but is not contractible. This will be useful in characterizing the form of the optimal incentive contract.

When repeated bilateral contracting takes place, a contract is usually considered to be robust to renegotiation if "at every contracting date, the continuation contract is an optimal solution to the continuation contracting problem for the remaining periods" (Bolton and Dewatripoint, 2004,). So, without loss of generality, we can restrict attention to contracts that are robust to renegotiation after the agent reveals the invention and before the principal implements the invention.

Definition 2 *A contract $w(\pi(t, z))$ is robust to renegotiation at $\widetilde{t}$ if, given $\widetilde{z}$ incentive compatible under $w(\cdot)$ and $\widehat{z}$ incentive compatible under an arbitrary contract $\widehat{w}(\pi(\widetilde{t}, z))$, the inequality $\widehat{w}(\pi(\widetilde{t}, \widehat{z})) > w(\pi(\widetilde{t}, \widetilde{z}))$ implies that $\pi(\widetilde{t}, \widehat{z}) - \widehat{w}(\pi(\widetilde{t}, \widehat{z})) \leq \pi(\widetilde{t}, \widetilde{z}) - w(\pi(\widetilde{t}, \widetilde{z}))$.A contract is said to be robust to renegotiation if it is robust to renegotiation for every invention t.*

A contract will be robust to renegotiation if and only if the efficient implementation $z^0(t)$ is chosen. This is because if a contract does not satisfy this condition, the principal and agent will renegotiate the contract to induce $z^0(t)$ and divide the gains between them. This insight has the important effect of placing a bound the slope of the contract.

Lemma 1. *A contract is robust to renegotiation if and only if* $[w(\pi)-w(\pi-\varepsilon)]/\varepsilon \leq 1$ *for every* π *and* $\varepsilon > 0$

Proof: As we have argued, a contract is robust to renegotiation if and only if it induces an implementation level $z^*(t) = z^0(t)$ for every t. So proving the lemma is equivalent to showing that a contract induces an implementation level $z^*(t) = z^0(t)$ for every t if and only if $[w(\pi) - w(\pi - \varepsilon)]/\varepsilon \leq 1$ for every π and $\varepsilon > 0$. The principal chooses z to maximize $v(t, z) = \pi(t, z) - w(\pi(t, z))$. Suppose to the contrary that $z^0(t)$ is not incentive compatible. Then, because $z^0(t)$ is the unique maximizer of $\pi(t, z)$ for any realization t, we can define $\varepsilon = \pi(t, z^0(t)) - \pi(t, z^*(t)) > 0$ for any $z^*(t)$ incentive compatible under $w(\cdot)$. Then, $[w(\pi) - w(\pi - \varepsilon)]/\varepsilon \leq 1$ for every π and $\varepsilon > 0$ implies that

$$\pi(t, z^0(t))-w(\pi(t, z^0(t))) = \pi(t, z^*(t))+\varepsilon-w(\pi(t, z^*(t))+\varepsilon) \geq \pi(t, z^*(t))-w(\pi(t, z^*(t))).$$

This contradicts the non-optimality of $z^0(t)$, so that $z^0(t)$ is incentive compatible for every t. Conversely, let $z^*(t) = z^0(t)$ for every t. Then, by similar arguments, the optimality of $z^0(t)$ implies $[w(\pi) - w(\pi - \varepsilon)]/\varepsilon \leq 1$. □

Contracts thus are robust to renegotiation if the principal's net return $\pi - w(\pi)$ is non-decreasing in the output π. This monotonicity result follows from Lemma 1. In what follows, we consider only contracts such that the principal's net return is nondecreasing. By Lemma 1, given $z^*(t) = z^0(t)$. Because $z^0(t)$ is strictly increasing in t, the innovative outcome is an increasing function of the invention t,

$$\Pi(t) = \pi(t, z^0(t)). \tag{11}$$

Because contracts that are robust to renegotiation, we can work with the innovation outcome function $\Pi(t)$.

This suggest the following highly useful principle.

Lemma 2. The implementation principle. *When contracts are robust to renegotiation and the principal implements an innovation after the agent reveals the invention, it is sufficient to consider an increasing innovative outcome function* $\Pi(t)$ *that depends only on the invention.*

This is a general result for moral hazard problems with endogenous implementation.[15] This result makes it easier to work directly with an outcome function that

[15] Later work will consider contracts when the parties can commit not to renegotiate. This is beyond the scope of the current paper.

depends only on the agent's report. The principal benefits from taking a greater number of samples because that increases the expected value of maximum order statistic.[16] Using the innovation outcome function, we characterize the form of the optimal incentive contract for R&D. We show that there is a reduced form contract that depends only on the invention. This is conceptually related to the "revelation principle" in adverse selection models that allows researchers to work with direct revelation mechanisms that are a function of the agent's type. Our approach allows researchers to work with outcome functions that are a function of the agent's report. This approach can be applied to solve a wide variety of moral hazard models and is a technical contribution of our analysis.

We show that the optimal incentive contract for delegated R&D takes the form of a call option.[17] The principal offers the agent a contract that specifies a threshold level of the outcome, $\pi = R$. If the outcome rises about the threshold, the agent obtains all of the benefits of the outcome net of the threshold and if the outcome is less than or equal to the threshold, the agent does not obtain any benefits,

$$w(\pi) = \max\{0, \pi - R\}. \tag{12}$$

Formally, a contract $w(\pi)$ is an *option* if satisfies the condition

$$\frac{\partial w(\pi)}{\partial \pi} = \begin{cases} 0 \text{ if } \pi < R, \\ 1 \text{ if } \pi > R. \end{cases} \tag{13}$$

To obtain our main results, we do not need to impose any further restrictions on the set of feasible contracts.

[16] Using integration by parts, the expected outcome equals

$$\int_0^\infty \Pi(t)h(t,n)dt = \Pi(0) + \int_0^\infty \Pi'(t)[1 - H(t,n)]dt.$$

Because $\Pi(t)$ is an increasing function and $H(t,n)$ is decreasing in n, the expected outcome is increasing in the number of samples,

$$\frac{\partial}{\partial n}\int_0^\infty \Pi(t)h(t,n)dt = -\int_0^\infty \Pi'(t)H_n(t,n)dt > 0.$$

[17] In finance, a call option is a contract that gives the owner the right but not the obligation to purchase a security at a given price, known as the strike price. The owner of the option will purchase the security only when the actual price rises above the strike price. The realized value of the call option is positive if and only if the actual price of the security rises above the strike price.

3 Simultaneous Sampling

This section considers the situation in which the agent designs the experiment by choosing the number of samples. Simultaneous sampling is used in many types of R&D such as clinical trials in pharmaceuticals and agricultural experiments. Researchers employ simultaneous sampling when the costs of taking multiple samples are less than the costs of waiting for additional observations that are associated with sequential sampling. Large-scale pharmaceutical trials typically involve simultaneous sampling because of the need to consider the effects of drugs on many patients. Simultaneous sampling also is useful in obtaining comparable observations in agricultural experiments when some conditions such as weather are not subject to control by the researcher.[18]

As a benchmark for evaluating delegated R&D, consider the number of samples that maximizes expected net benefits

$$n^0 \in \arg\max_a \int_0^\infty \Pi(t)h(t,a)dt - ca.$$

The optimal number of samples n^0 is the largest number n such that $-\int_0^\infty \Pi'(t)H_n(t,n)dt \geq c$. The optimality condition is equivalent to the expectation of the critical ratio $\gamma(\Pi, n)$ multiplied by the marginal effect of the invention on profit divided by the hazard rate,

$$\int_0^\infty \gamma(\Pi(t), n)\frac{\Pi'(t)}{r(t,n)}h(t,n)dt \geq c.$$

With delegated R&D, the principal faces a trade-off between the benefits of additional sampling and the costs of giving incentives to the agent. Given a contract $w(\pi)$, the expected utility of the agent and the principal are given by

$$U(w,n) = \int_0^\infty w(\Pi(t))h(t,n)dt - cn - u_0, \tag{14}$$

$$V(w,n) = \int_0^\infty [\Pi(t) - w(\Pi(t))]h(t,n)dt. \tag{15}$$

The principal's problem of choosing an optimal contract, w, subject to feasibility restrictions can be stated as follows,

$$\max_{w,n} V(w,n) \tag{16}$$

[18] R&D models in which an economic actor chooses the number of simultaneous samples include Tan (1992), Fullerton and McAfee (1999), Baye and Hoppe (2003), Fu and Lu (2012), and Fu et al. (2012).

subject to

$$n \in \arg\max_a U(w,a), \tag{17}$$

$$U(w,n) \geq 0, \tag{18}$$

$$w(\pi) \geq 0, \text{ for all } \pi, \tag{19}$$

$$[w(\pi+\varepsilon) - w(\pi)]/\varepsilon \leq 1, \text{ for all } \pi. \tag{20}$$

The first constraint is the agent's incentive compatibility condition for the agent's choice of effort, n, the second constraint is the agent's individual rationality condition, and the third constraint represents the agent's limited liability. The last constraint follows from the requirement of robustness to renegotiation that limits the slope of the contract, w.

We now state the first of our two main results.

Proposition 1. *The optimal incentive contract for delegated R&D with simultaneous search takes the form of an option.*

Proof: We first show that given any continuous contract, there always exist a better contract that takes the form of an option. Take an arbitrary continuous contract w that is not an option and that induces the agent to choose $\widehat{n} \geq 1$ draws.[19] Consider an option contract $\widehat{w}(\pi)$ that yields the same net expected benefits for the agent for that $\widehat{n}$, $U(\widehat{w},\widehat{n}) = U(w,\widehat{n})$. Because $\Pi(t)$ is increasing, the value of the maximum $\widehat{t}$ that satisfies $\Pi(\widehat{t}) = \widehat{\pi}$ is well defined. Remember that

$$U(w,n) = \int_0^\infty w(\Pi(t))h(t,n)dt - cn - u_0.$$

Integrating by parts gives

$$U(w,n) = \int_0^\infty w'(\Pi(t))\Pi'(t)[1 - H(t,n)]dt - cn - u_0. \tag{21}$$

Differentiating with respect to n implies

$$\frac{\partial U(w,n)}{\partial n} = -\int_0^\infty w'(\Pi(t))\Pi'(t)H_n(t,n)dt - c.$$

Noting that $U(\widehat{w},\widehat{n}) = U(w(\bullet),\widehat{n})$, adding $U(\widehat{w},\widehat{n}) - U(w,\widehat{n})$ implies

$$\frac{dU(\widehat{w},\widehat{n})}{dn} - \frac{dU(w,\widehat{n})}{dn} = \int_0^\infty \Pi'(t)[\widehat{w}'(\Pi(t)) - w'(\Pi(t))]\left[\frac{H_n(t,\widehat{n})}{1-H(t,\widehat{n})} - \frac{H_n(\widehat{t},\widehat{n})}{1-H(\widehat{t},\widehat{n})}\right](1 - H(t,\widehat{n}))dt.$$

[19] By assumption, the optimal contract does not induce the agent to choose $n = 0$ draws.

Therefore, we can write this as

$$\frac{dU(\widehat{w},\widehat{n})}{dn}-\frac{dU(w,\widehat{n})}{dn} = \int_0^{\widehat{T}} -w'(\Pi(t))]\Pi'(t)\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right](1-H(t,\widehat{n}))dt + \int_{\widehat{T}}^{\infty}[1-w'(\Pi(t))]\Pi'(t)\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right](1-H(t,\widehat{n}))dt$$

The second term $\int_{\widehat{T}}^{\infty}[1-w'(\Pi(t))]\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right](1-H(t,\widehat{n}))dt$ is positive

because $w'(\bullet)$ is restricted to be less than one. To prove that the first term is positive , notice that

$$\frac{\partial}{\partial t}\left[\left(\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right)(1-H(t,\widehat{n}))\right] = \frac{\partial\gamma(\Pi(t),\widehat{n})}{\partial t}(1-H(t,\widehat{n}))-h(t,\widehat{n})\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right].$$

So, $\left[\left(\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right)(1-H(t,\widehat{n}))\right]$ is negative and increasing in $(0,\widehat{t})$. Integrating by parts and noting that at $\widehat{t}$ the value of the function is 0,

$$\int_0^{\widehat{t}} -w'(\Pi)\Pi'(t)\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right](1-H(t,\widehat{n}))dt = \int_0^{\widehat{t}} w(\Pi)\frac{\partial}{\partial t}\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right](1-H(t,\widehat{n}))dt.$$

Clearly this integral will be positive since $w(\Pi)>0$ by the limited liability constraint and we already showed that $\frac{\partial}{\partial t}\left[\gamma(\Pi(t),\widehat{n})-\gamma(\Pi(\widehat{t}),\widehat{n})\right](1-H(t,\widehat{n}))$ is positive. We therefore know that $\frac{dU(\widehat{w}(\pi),n)}{dn}>\frac{dU(w,n)}{dn}$ at $\widehat{n}$.

Consider now the case when $1\leq\widetilde{n}\neq\widehat{n}$ (not necessarily an integer) and suppose that $U(w,\widetilde{n})=U(\widehat{\pi},\widetilde{n})$ holds. We can rewrite the equation as

$$\frac{dU(\widehat{w},\widetilde{n})}{dn}-\frac{dU(w,\widetilde{n})}{dn}=\int_0^{\infty}\Pi'(t)[\widehat{w}'(\Pi(t))-w'(\Pi(t))][\gamma(\Pi(t),\widetilde{n})-\gamma(\Pi(\widehat{t}),\widetilde{n})](1-H(t,\widehat{n})))dt. \tag{22}$$

Given the definition of $\widetilde{t}$, this expression is positive when evaluated at $\widetilde{n}$. Therefore, whenever a contract gives the same net benefits as an option we have that $\frac{dU(\widehat{w},n)}{dn}>\frac{dU(w,n)}{dn}$. It is well-known that if two functions satisfy the property that whenever they are equal, the slope of one of them is larger, then they cross at most once for $n\geq1$. The single-crossing property implies that $U(\widehat{w},n)=U(w,n)$ can only hold at $\widehat{n}$. The single-crossing property of U has several implications. For these implications consider that we now restrict attention to integers greater than or equal to one. (i) If $\widehat{n} \in \arg\max_x U(w, x)$ and $n' \in \arg\max_x U(\widehat{w}, x)$, then $n' \geq \widehat{n}$. (ii) Letting

$$U(w) = \max_{n \in \mathbb{Z} \geq 1} \int_0^\infty w(\Pi(t))h(t, n)dt - cn - u_0 \tag{23}$$

single-crossing at $\widehat{n}$ implies $U(\widehat{w}) \geq U(w)$. (iii) If $\widehat{n} \in \arg\max_a U(w, a)$ and $n' \in \arg\max_a U(\widehat{\pi}, a)$, letting $V(w) = V(w, \widehat{n})$ and $V(\widehat{w}) = V(\widehat{w}, n')$ implies that $V(\widehat{w}) \geq V(w)$. This is because from (i), $n' \geq \widehat{n}$, which implies that $V(w, \widehat{n}) = V(\widehat{w}, \widehat{n}) \leq V(\widehat{w}, n')$.

From (ii) and (iii), the contract $\widehat{w}$ generates no less benefits for the principal than does the contract w, and satisfies the agent's individual rationality constraint. This implies that there always exists an option contract that outperforms any continuous contract.

Finally, we claim that no discontinuous contract can strictly outperform all option contracts because discontinuous contracts can have only discontinuities of the first type and can be approximated with continuous contract. So, if there exists an optimal contract there must exist an optimal option contract. Existence follows because the space of option contracts that satisfy the participation constraint is compact. $\square$

The intuition for Proposition 1 is as follows. Because the "implementation principle" holds, the manager only needs to consider the innovative outcome as a function of the realization of the invention. Also, in equilibrium, the manager's implementation decision will be efficient after the invention is realized. This simplifies the manager's contract design problem to the choice of rewards for the researcher based on the market value of the innovation rather than the underlying invention.

To, establish Proposition 1, we obtain a single-crossing condition, which shows that the contract takes the form of an option. Because of the "implementation principle," the contract can be expressed as a non-decreasing function of the underlying invention,

$$W(t) = w(\Pi(t)) = \max\{0, \Pi(t) - R\}.$$

The manager uses an option because it shifts rewards to the highest-quality inventions. The induced outcome distribution satisfies DHREP, which implies that it is better to induce effort by increasing the slope of the contract for higher output values. This yields an incentive contract that is easy to apply within organizations and between companies.

The characteristics of the optimal contract are based on the properties of the maximum order statistic and the increasing inverse of the outcome function. Define $t = \tau(\Pi)$ as the inverse of $\Pi = \Pi(t)$. The distribution of the maximum order statistic induces a reduced-form distribution of the outcome Π for any given sample size n,

$$G(\pi, n) = H(\tau(\pi), n). \tag{24}$$

Letting $g(\pi, n) = \frac{\partial G(\pi,n)}{\partial \pi}$ denote the density of the reduced-form distribution, define the hazard rate of the reduced-form distribution$\frac{g(\pi,n)}{1-G(\pi,n)}$.The hazard rate of the reduced-form distribution has a useful multiplicative decomposition. The hazard rate equals the slope of the inverse of the outcome function times the hazard rate of the maximum order statistic,

$$\frac{g(\pi, n)}{1 - G(\pi, n)} = \tau'(\pi) r(\tau(\pi), n). \tag{25}$$

As we showed above, the distribution $h(\tau, n)$ always satisfies DHREP and so the induced output distribution also satisfies DHREP.

With delegated R&D the agent chooses n^* samples. The agent's marginal incentive for effort excluding effort costs can be rewritten using the critical ratio,

$$\frac{\partial U(w, n)}{\partial n} = \int_0^\infty w'(\Pi(t))\Pi'(t)\gamma(t, n)(1 - H(t, n))dt - c. \tag{26}$$

This can be rewritten using the hazard rate,

$$\frac{\partial U(w, n)}{\partial n} = \int_{\tau(\widehat{\pi})}^\infty \gamma(\Pi(t), n)\frac{\Pi'(t)}{r(t, n)}h(t, n)dt - c. \tag{27}$$

Comparing this expression with the first-order condition for the optimal number of samples, notice that with delegated R&D the agent only is rewarded for the highest quality inventions. This implies that the marginal return to effort is decreased by delegation.

Corollary 1. *With simultaneous sampling, the agent shirks by taking fewer than the optimal number of samples,* $n^* \leq n^0$.

The marginal return to sampling for the agent net of sampling costs can be written using the covariance between the critical ratio and the marginal effect of the sufficient statistic on the agent's reward divided by the hazard rate. When the agent's participation constraint is binding, this implies that the marginal return to sampling is greater than the covariance net of unit sampling costs,

$$\frac{\partial U(w,n)}{\partial n} - [cov\left(\gamma(\Pi(t),n), \frac{w'(\Pi(t))\Pi'(t)}{r(t,n)}\right) - c] = (cn+u_0)E\gamma(\Pi(t),n) > 0.$$

Shirking by the agent reduces the quality of the invention, which in turn reduces the manager's implementation effort, with both forces thus reducing the quality of innovation.

4 Sequential Sampling

This section considers the optimal incentive contract for R&D when the agent engages in sequential sampling. Researchers employ sequential sampling when the costs of taking additional samples outweigh the costs of waiting for additional samples. Sequential sampling allows for learning and is used in many types of repeated scientific experiments.[20] Sequential sampling corresponds to economic models of searching for the highest sample from a distribution. The use of computer simulations in experiments affect the relative costs of parallel and sequential sampling in R&D (Thomke et al. 1998).

Let t be the realization of a draw from the distribution $F(x)$. Sequential sampling results in a delay of one period for each sample and the discount factor is δ, where $0 < \delta < 1$. As a benchmark for evaluating delegated R&D, consider the stopping rule that maximizes the principal's expected net benefits without delegation. The researcher stops the R&D process when the realized benefit $\Pi(t)$ exceeds a critical level.

Because the benefit is an increasing function by the "implementation principle," the stopping rule can be expressed in terms of t. The utility of the researcher , given a stopping rule $\widetilde{t}$ is

$$\frac{1}{1-\delta F(\widetilde{t})}[\delta \int_{\widetilde{t}}^{\infty} \Pi(t)f(t)dt - c].$$

The optimal stopping rule t^0 satisfies the standard recursive equation,

$$\Pi(t^0) = -c + \delta \int_{t^0}^{\infty} \Pi(t))f(t)dt + \delta F(t^0)\Pi(t^0). \tag{28}$$

Rearranging terms simplifies the optimal recursive condition,

$$\Pi(t^0) = \frac{1}{1-\delta F(t^0)}[\delta \int_{t^0}^{\infty} \Pi(t)f(t)dt - c]. \tag{29}$$

[20]See Wald (1950) on the development of sequential analysis.

With delegated R&D, the optimal incentive contract is designed to induce the agent to choose the best possible stopping rule. The agent´s expected utility given a contract $w(\bullet)$, and a stopping rule $\widetilde{t}$ is

$$U(w,\widetilde{t}) = \frac{1}{1-\delta F(\widetilde{t})}[\delta \int_{\widetilde{t}}^{\infty} w[\Pi(t)]f(t)dt - c] - u_0 \tag{30}$$

The agent chooses a stopping rule t^* that satisfies the recursive condition

$$w(\Pi(t^*)) = -c + \delta \int_{t^*}^{\infty} w(\Pi(t))f(t)dt + \delta F(t^*)w(\Pi(t^*)). \tag{31}$$

Rearranging terms gives

$$w(\Pi(t^*)) = \frac{1}{1-\delta F(t^*)}[\delta \int_{t^*}^{\infty} w(\Pi(t))f(t)dt - c]. \tag{32}$$

We can write the expected utility of the agent as a function of the stopping rule t^*, $U(w,t^*) = w(\Pi(t^*)) - u_0$.

Given the stopping rule t^*, expected output equals

$$\Gamma(t^*) = \frac{\delta}{1-\delta F(t^*)} \int_{t^*}^{\infty} \Pi(t)f(t)dt. \tag{33}$$

The principal's expected net benefit is then

$$V(w,t^*) = \Gamma(t^*) - w(\Pi(t^*)) = \frac{1}{1-\delta F(t^*)}\{\delta \int_{t^*}^{\infty} [\Pi(t) - w(\Pi(t))]f(t)dt + c\}. \tag{34}$$

The principal's problem of choosing an optimal contract, w, subject to feasibility restrictions then takes the form,

$$\max_{w,t^*} V(w,t^*) \tag{35}$$

subject to

$$t^* \in \arg\max_{\zeta} U(w,\zeta), \tag{36}$$

$$U(w,t^*) \geq 0, \tag{37}$$

$$w(\pi) \geq 0, \text{ for all } \pi,$$

$$[w(\pi+\varepsilon) - w(\pi)]/\varepsilon \leq 1, \text{ for all } \pi. \tag{38}$$

If the reported statistic were verifiable and there was no need to implement the invention, the contracting problem could be readily solved using a basic forcing contract.[21] However, the need to implement the invention does not allow for the contract to have upward jumps or a slope greater than one. The proof as before shows that any continuous contract can be outperformed by an option.

We now state our second main result.

Proposition 2. *The optimal incentive contract for delegated R&D with sequential search takes the form of an option.*

Proof: Suppose to the contrary that the optimal contract, w, is not an option and that it induces the agent to choose a stopping rule $\widetilde{t}$. Consider an option contract $\widehat{w}(\cdot)$, with strike price R that yields the same net benefits for the agent for that stopping rule $\widetilde{t}$, $U(\widehat{w},\widetilde{t}) = U(w,\widetilde{t})$. This implies that

$$\int_{\widetilde{t}}^{\infty} w(\Pi(t))f(t)dt = \int_{\widetilde{t}}^{\infty} [\Pi(t) - R]^{+} f(t)dt. \tag{39}$$

Notice first that it must be the case that $\Pi(\widetilde{t}) \geq R$. If $\Pi(\widetilde{t}) < R$, then $\widehat{w}(\Pi(\widetilde{t})) = 0$, which means that $\widetilde{t}$ does not solve the recursive optimality equation for $\widehat{w}(\cdot)$, and then because by construction $U(\widehat{w},\widetilde{t}) = U(w,\widetilde{t})$,the call option satisfies the participation constraint and induces a higher stopping rule $t^{*} > \widetilde{t}$, which increases the principal´s utility and thus contradicts optimality of $w()$.

Integrating by parts (39) using the fact that $\Pi(\widetilde{t}) \geq R$, implies that

$$\int_{\widetilde{t}}^{\infty} w'(\Pi)\Pi'(t)\left[1 - F(t)\right] dt + w(\widetilde{\Pi})[1 - F(\widetilde{t})] = \int_{\widetilde{t}}^{\infty} \Pi'(t)\left[1 - F(t)\right] dt + [\Pi(\widetilde{t}) - R][1 - F(\widetilde{t})].$$

Because $w'(\Pi) \leq 1$, this implies that

$$[\widetilde{\pi} - R]^{+} < w(\widetilde{\pi}). \tag{40}$$

Differentiating the agent's utility (30) with respect to the stopping rule $\widetilde{t}$ gives

$$\frac{\partial U(w,\widetilde{t})}{\partial \widetilde{t}} = \frac{f(\widetilde{t})}{1 - \delta F(\widetilde{t})}\left[U(w,\widetilde{t}) + u_0 - w(\widetilde{\pi})\right].$$

[21] The least-cost way to implement a stopping rule, say t^0, would be to choose a contract $\zeta(t)$ of the form

$$\zeta(t) = \begin{cases} u_0 + \delta \frac{c}{1 - F(t^0)} & \text{if } t > t^0, \\ 0 \text{ otherwise.} \end{cases}$$

This contract would induce the agent to stop the search at t^0.

Noting that $U(\widehat{w},\widetilde{t}) = U(w,\widetilde{t})$, implies

$$\frac{dU(\widehat{w},\widetilde{t})}{d\widetilde{t}} - \frac{dU(w,\widetilde{t})}{d\widetilde{t}} = \frac{f(\widetilde{t})}{1-\delta F(\widetilde{t})}\left[w(\widetilde{\pi}) - [\widetilde{\pi} - R]^{+}\right].$$

By (40)this term is positive at $\widetilde{t}$. Moreover, we can repeat the argument whenever $U(\widehat{w},\widetilde{t}) = U(w,\widetilde{t})$. This means that whenever $U(\widehat{w},t) = U(w,t)$ and $\Pi(\widetilde{t}) \geq R$, $\frac{dU(\widehat{w},t)}{dt} > \frac{dU(w,t)}{dt}$. Also, it is well known that two functions cross at most once if the slope of one of the functions is greater than the other whenever they are equal. The single-crossing property of U has several implications. (i) Letting

$$U(w) = \max_{t} U(w,t) \tag{41}$$

single-crossing at $\widetilde{t}$ implies $U(\widehat{w}) \geq U(w)$. (ii) If $t^{w} \in \arg\max_t U(w,t)$ and $t^{\widehat{w}} \in \arg\max_t U(\widehat{w},t)$, single crossing implies that $t^{\widehat{w}} > t^{w}$.(iii) Letting $V(w) = V(w,t^{w})$ and $V(\widehat{w}) = V(\widehat{w},t^{\widehat{w}})$ implies that $V(\widehat{w}) \geq V(w)$. This is because from (ii), $t^{\widehat{w}} \geq t^{w}$, which implies that $V(w,t^{w}) = V(\widehat{w},t^{w}) < V(\widehat{w},t^{\widehat{w}})$.

From (i) (ii) and (iii), the contract $\widehat{w}$ generates benefits for the principal that are not less than those generated by the contract w and satisfies the agent's individual rationality constraint. For the same arguments as in Proposition 1, this implies that if there exists an optimal contract, there also exists an optimal option contract. Existence follows because the space of option contracts that satisfy the participation constraint is compact. □

Although sequential sampling differs from simultaneous sampling, the intuition for the proofs are similar for both types of experimental design. We again obtain a single-crossing condition for the agent's benefit. We show that the efficient contract with sequential search puts the most weight on the best outcomes. By the "implementation principle," the manager's implementation decision will be optimal given the realization of the invention. Therefore, we can again restrict attention to contracts that depend on the realization of innovation, where innovation is viewed as a function of the quality of the underlying invention.

Proposition 2 shows that the contract can be expressed again as an option $W(t) = w(\Pi(t)) = \max\{0, \Pi(t) - R\}$. The contract is again non-decreasing in the quality of the invention. Also, Propositions 1 and 2 show that the optimality of the option contract is robust to the type of experiment performed by the agent.

Consider now the agent's incentives for performance with sequential sampling. It must be the case that $\Pi(t^{*}) > R$ because otherwise the agent would not expect to receive benefits from search, $w(\Pi(t^*)) = 0$, and the recursive equation would not hold. From the implementation principle, $\Pi(t)$ increasing implies that $\Pi(t) > R$ for $t > t^*$.The recursive equation thus implies that at the optimal strike price R, the optimal stopping rule t^* solves

$$\Pi(t^*) - R = \frac{1}{1-\delta F(t^*)}[\delta \int_{t^*}^{\infty} (\Pi(t) - R) f(t) dt - c]. \tag{42}$$

The recursive equation can be rewritten as follows,

$$\Pi(t^*)(1 - \delta F(t^*)) - \delta \int_{t^*}^{\infty} \Pi(t) f(t) dt + c = R(1-\delta) > 0. \tag{43}$$

Notice that as the discount factor δ approaches one, the stopping rule approaches the first best. The term $\Pi(t)(1 - \delta F(t)) - \delta \int_t^{\infty} \Pi(t) f(t) dt$ is increasing in t. This implies that the agent sets the stopping rule above the optimal level so that the realized benefit $\Pi(t^*)$ exceeds the first-best critical level, $\Pi(t^0)$, and the agent spends too much time searching.

Corollary 2. *With sequential sampling, the stopping rule with delegated R&D t^* is greater than the first-best t^0, so the agent samples more than is optimal.*

The optimal stopping rule is greater than the inverse of the outcome function evaluated at the strike price, $t^* > \tau(R)$. Because the optimal contract is an option, the principal's expected net benefit can be written as a function of the strike price,

$$V(w, t^*) = \frac{1}{1-\delta F(t^*)}[\delta R(1 - F(t^*)) + c]. \tag{44}$$

When the agent's participation constraint is binding, the strike price exactly equals the difference between profit at the stopping rule and the agent's opportunity cost, $R = \Pi(t^*) - u_0$.

Proposition 2 continues to hold if the agent takes a given number of samples N in each period. The distribution of the best observation in each period is $F^N(t)$ and the recursive equation is

$$\Pi(t^*) - R = \frac{1}{1-\delta F^N(t^*)}[\delta \int_{t^*}^{\infty} (\Pi(t) - R) N F(t)^{N-1} f(t) dt - cN]. \tag{45}$$

For any given number of samples per period, the agent still engages in too much sampling, so that Corollary 2 still holds.

5 Extensions

This section considers three extensions of the analysis. We first consider the choice of experimental design in terms of selecting distributions from which to sample. We next consider the choice of the number of samples when the principal cannot perfectly observe the sample statistics.Then, we consider the researcher´s effort when the number of samples is a random variable.

5.1 Experimental Design

Delegated R&D involves other considerations besides sample size. In particular, the agent must choose among different experimental designs. Blackwell (1951,1953) considers the choice of how to sample within a population and suggests that the statistician should use the most informative experimental design. Our analysis suggests that in addition to considerations of informative distributions, a statistician should take into account the costs of a more informative experimental design. These costs might include the costs of more precise equipment and the costs of additional data gathering and processing associated with sampling from different distributions. Our analysis further suggests that when a principal delegates R&D, the choice of an experimental design also depends on the agency costs of inducing effort from the researcher.

The experimental design problem can be seen as choosing among m different distributions from which to sample, $H_1(t,n)$, $H_2(t,n)$, ... , $H_m(t,n)$. To illustrate this problem separately from the sampling, let the sample size n be fixed and suppose that it is common knowledge. As before, the researcher reports the maximum value of the sample, $t(X) = \max\{x_1, x_2, ..., x_n\}$. Suppose that the distributions differ in terms of the scale of the distribution, s_j,

$$H_j(t,n) = H(t, s_j, n) = F^n(\frac{t}{s_j}). \tag{46}$$

The scale of the distribution is a measure of dispersion. For example, in the normal distribution the scale is equal to the standard deviation σ. Because the principal benefits from the largest observation, the principal derives benefits from distributions with a higher scale.

Order the family of distributions in terms of their scale and treat effort as a continuous variable. Suppose that the researcher's effort determines the scale of the distribution

s at a cost of cs.Then, the researcher's choice of effort s corresponds to choosing among distributions and represents the experimental design. The hazard rate is then

$$r(t,s,n) = \frac{h(t,s,n)}{1-H(t,s,n)}. \tag{47}$$

As before, the principal's profit is $\Pi = \pi(t,z)$ and satisfies Assumptions 1 and 2, so that $\Pi(t)$ is an increasing function. The cumulative distribution is decreasing in the scale of the distribution,

$$H_s(t,s,n) = -nF^{n-s}(\frac{t}{s})\frac{t}{s^2}f(\frac{t}{s}) < 0.$$

Therefore, effort devoted to increasing the scale of the distribution increases the principal's expected return

$$\frac{\partial}{\partial s}\int_0^\infty \Pi(t))h(t,s,n)dt = -\int_0^\infty \Pi'(t))H_s(t,s,n)dt > 0$$

Shirking by the researcher affects the choice of the distribution. With delegated R&D, the scale of the distribution will be less than the full-information optimal scale.

As an illustration, consider the design of experiments to determine reliability. Suppose that a researcher conducts an experiment to determine the failure rate of a product or technology and reports the reliability to the principal. The family of distributions is given by the Weibull distribution, which is often used to model experimental failure rates. Let $x \geq 0$ represent the observed date of failure. Normalize the shape of the distribution to equal one so that the failure rate is constant over time.[22] Then, the distribution of the reliability x is given by $F(x,s) = 1 - e^{\frac{-x}{s}}$. The hazard rate satisfies DHREP in s. For $n = 1$ we have $r_s(t,s,n) < 0$ and for $n > 1$, we have

$$r_s(t,s,n) = r(t,s,n)\frac{t}{s^2}[-\frac{s}{t} - sr(t,s,n) - (n-1)\frac{e^{\frac{-t}{s}}}{1-e^{\frac{-t}{s}}} + 1] < 0.$$

From Proposition 1, this implies the following.

Corollary 3. *When the researcher's effort increases the scale of the distribution, the optimal incentive contract for delegated R&D with simultaneous search takes the form of an option.*

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[22] The Weibull distribution is generally written as $F(x,s) = 1 - e^{\frac{-x^\xi}{s}}$ where $\xi > 0$ represents the shape of the distribution. If ξ is greater than, equal to, or less than one, then the failure rate is increasing, constant, or decreasing over time.

This implies that an option contract can be used to induce the agent to choose the experimental design.

The analysis of experimental design can be extended to the sequential choice of distinct distributions from which to sample. One approach to the design of the experiment is to order the distributions and to sample from each of them in turn with the possibility of stopping if a desirable outcome is observed. This generates a stopping rule that is similar to that for sequential sampling from the same distribution, see Weitzman (1979) and Spulber (1980). The present analysis suggests that with delegated R&D and sequential sampling, the researcher will choose to sample from more distributions than is optimal without delegation.

5.2 Imperfect observation of experimental results

Suppose that the principal cannot perfectly observe the outcome of the experiment. The researcher reports $t(X)$ and the principal observes

$$y = \theta + t, \tag{48}$$

where θ is a shock with cumulative distribution function $\Psi(\theta)$ and density $\psi(\theta)$ on $[0, \infty)$. The shock θ is independent of t. Assume that the shock θ has a log-concave failure rate $1 - \Psi(\theta)$, which implies that it has an increasing hazard rate $\frac{\psi(\theta)}{1-\Psi(\theta)}$.

The shock is realized when the researcher reports t and is unknown to both the principal and the agent. The principal can only contract with the agent on the basis of the observed outcome y. An implementation $z^*(y)$ is incentive compatible for the principal at y under contract $w(\pi)$ if $z^*(y) \in \arg\max_z \Pi(y, z) - w(\Pi(y, z))$. The agent anticipates the effect of the realization of the statistic on the principal's implementation decision $z^*(\theta + t(X))$. It follows that the principal's return $\Pi(y)$ is increasing in the outcome y.

The density of the sum y is given by the convolution of the density of the shock $\psi(\theta)$ and the density of the statistic $h(t, n)$,

$$b(y, n) = \int_0^y \psi(y - x) h(x, n) dx. \tag{49}$$

Let $B(y, n) = \int_0^y [\int_0^z \psi(z - x) h(x, n) dx] dz$ be the cumulative density of y. Define the hazard rate function for the convolution, $r(y, n) = \frac{b(y,n)}{1-B(y,n)}$. Because the shock θ is independent of t and has a logconcave failure rate, it follows that the convolution has a hazard rate that is decreasing in n, $r(y,n) > r(y,n+1)$. This is obtained by noting from Lemma 1.B.3 in Shaked and Shantikumar (2007, p. 18) that if a random variable dominates another random variable in the hazard rate order, the order is preserved by adding a shock with an increasing hazard rate. Therefore, the distribution $B(y,n)$ satisfies DHREP.

With simultaneous search, the expected utility of the agent and the principal are given by

$$U(w,n) = \int_0^\infty w(\Pi(y))b(y,n)dy - cn - u_0,$$

$$V(w,n) = \int_0^\infty [\Pi(y) - w(\Pi(y))]b(y,n)dy. \tag{50}$$

The imperfect observability of experimental results by the principal does not change the form of the incentive contract. By arguments similar to those in Proposition 1, we obtain the following result.

Corollary 4. *When the agent's report is imperfectly observed by the principal, the optimal incentive contract for delegated R&D with simultaneous search takes the form of an option.*

When the principal cannot perpectly observe the agent;s report, moral hazard effects continue to hold with simultaneous sampling. The researcher will devote less than optimal effort to generating a random number of observations.

5.3 Random Number of Observations

The number of observations may be random in various types of experiments and statistical analysis. This occurs, for example, when studying random processes for a fixed period of time (Anscombe, 1952, Gut, 2012). Summing a random number of observations yields random sums, which are used in the random-sum strong law of large numbers and the random-sum central limit theorem (Gut, 2012). Random sums are useful in various types of experiments for determining "fatigue damage" in mechanical and electrical systems (Mallor and Omey, 2001).

Suppose that the statistic consists of a random sum,

$$t(X,m) = \sum_{i=1}^m x_i,$$

where m is a discrete random variable. Assume that the random variables X_i are indepedendantly and identically distributed with cumulative distribution $F(x)$. Suppose that the failure rate $1 - F(x)$ is log-concave so that the hazard rate $\frac{f(x)}{1-F(x)}$ is increasing. Suppose that the conditional likelihood of obtaining m observations $\rho(m, a)$ is decreasing in the researcher's effort a, where

$$\rho(m, a) = \frac{P(Y = m, a)}{1 - P(Y \leq m, a)}$$

The researcher's effort is continuous and has a cost ca. The probability distribution of the random sum $h(t, a)$ satisfies DHREP (based on an application of Shaked and Shanthikumar, 2007, Theorem 1.B.7, p. 20). This implies the following result

Corollary 5: W*ith random numbers of observations, the optimal incentive contract for delegated R&D takes the form of an option.*

Due to moral hazard effects, the researcher will devote less than optimal effort to generating a random number of observations.

6 Management of IP and Financing of R&D

Our finding that the optimal contract for delegated R&D takes the form of an option has some useful implications for company management of IP. Companies generally own the inventions generated by their employees. Employment contracts tend to assign ownership of patents to employers and as do default rules in state laws governing employment (see Merges, 1999, for an overview). Unlike copyright, there is no work-for-hire doctrine in patent law (Merges, 1999, Burk, 2004). Managers must determine how to provide incentives to researchers conducting delegated R&D when the firm will own the resulting invention.

The optimal incentive contract obtained in our analysis provides insights in management of R&D when the firm owns the inventions generated by R&D. The optimal contract can be interpreted as a call option in which an employee has a right but not an obligation to purchase the innovative project . Inventions belong to the principal, but the employee owns an option to buy the invention at a price R. The option contract specifies the lump-sum payment to the firm, which corresponds to the strike price of an option contract. Call options on the firm´s value are often used in providing inventives to research units within firms. Lerner and Wolf (2007) show that companies using option contracts to reward innovation are associated with more patent filing and more cited patents that firms using other incentive schemes.

The option contract in our setting also corresponds to spin-offs in which the employee starts a new firm and compensates the employer for knowledge acquired at the parent company. The firm creating the spin-off provides financing to the new venture. In this setting, the firm and the employee cooperatively implement the invention by establishing the new firm. This corresponds to developing the invention in the present model represented by the principal's choice of z. The optimal agency contract provides the employee with incentives to devote effort to invention and also gives the principal incentives to invest efficiently in the venture after the discovery is made. Our analysis suggests that small innovations will be performed by the firm (intrapreneurship) and significant innovations will result in spin-offs (entrepreneurship) so as to provide incentives to the researcher based on the best outcomes.

The present analysis offers insights into commercialization of IP and innovative decisions by firms, entrepreneurs, and independent inventors. Setting aside delegated R&D within the firm, it is useful to consider managers' strategic innovation decisions. After developing an invention, managers encounter additional costs of commercializing the invention including costs of marketing, selling, and licensing the invention, costs of developing a product using the invention, legal and administrative costs of maintaining patent rights, and legal costs of defending against infringement. Managers will commercialize IP or develop inventions only if expected returns excced the costs of commercialization or innovation. Suppose that these costs are exogenous to the firm and are represented by a lump sum R. Then, the manager will choose to commercialize IP if and only if market returns π exceed the costs R of commercializing IP.

Various studies have considered the role of options in R&D. Pakes (1986) observes that when inventors must pay fees to maintain their patents, such IP rights function as options because inventors will only choose to renew the patents when their value exceeds the renewal fee. Erkal and Scotchmer (2009) suggest that innovation is an option that is exercised when the returns to developing an idea exceed the costs of investing in the idea. Ziedonis (2007) considers contracts offered by firms that sponsor R&D conducted by university researchers that give the firm an option to purchase the invention. Our analysis of the incentive contract is consistent with these observations. Our analysis suggests that managers making strategic innovation decisions will devote insufficient effort to innovation when engaged in simultaneous sampling and will devote excessive effort when engaged in sequential sampling.

Option contracts also can improve incentives for R&D investment with contract renegotiation. Effects on investment incentives of options to purchase are also considered by Demski and Sappington (1991). Our analysis sheds some light on technology transfer contracts including assignment and licensing of patents. Standard royalty contracts involve either a lump-sum payment, a payment per-unit of output, or some combination of the two, which provides a means of metering market demand for the technology. The combination of lump-sum and per-unit royalties is used to maximize the IP owner's returns from commercializing a given invention *after* R&D has taken place. However, our analysis does suggest that technology transfer contracts that involve additional R&D to further develop the invention should take the form of option contracts. Jensen and Thursby (2001) find that more than 70 percent of university inventions are sufficiently "embryonic" that after transferring the license to a firm, the inventor must provide additional effort to improve the probability of commercial success. Jensen and Thursby (2001) also examine payments included in university license transfers and find that fixed fees (license-issue or annual) and proportional royalties appear in roughly 80 percent of the license agreements, with fixed fees accounting for 13 percent of revenue received and royalties accounting for 75 percent, along with commonly-used milestone payments and patent reimbursement. They also find that agreements that include equity also tend to include fixed fees and proportional royalties.

Financing of company R&D can be subject to moral hazard problems (Hall, 2002). Our analysis suggests that these incentive problems can be addressed with option contracts. Option contracts for delegated R&D are consistent with incentives for innovative entrepreneurs who obtain financing from banks or venture capitalists. Entrepreneurs often obtain debt financing from banks. Debt is a type of option contract in which the strike price is the face value of the debt and the borrower retains earnings in excess of the face value of the debt. Kaplan and Strömberg (2003) observe that venture capitalists often use convertible preferred securities to finance startups that function like option contracts.

There is increasing financing for independent inventors and startup firms engaged in R&D. Our results suggest that debt contracts can be useful in financing R&D because they have the form of a call option and thus are optimal contracts for R&D when the researcher's effort is unobservable to investors. In addition, financial valuation techniques can be used to calculate the value of options, which suggests that there may be ways to value debt contracts used to finance R&D. Option contracts can be readily standardized, which should facilitate the exchange of contracts used to finance R&D in the same way that financial options are traded on organized exchanges.

7 Conclusion

The management of invention and innovation contributes substantially to company value and competitive strategy. Our analysis suggests that managers should consider the interaction between delegated R&D and innovative application of inventions generated by R&D. Managers should pay careful attention to the design of incentives provided to specialized personnel engaged in R&D and contracts for external providers of R&D. The option contract design that we obtain is relatively straightforward because it resembles financial options and debt-style contracts. Additionally, option contracts for researchers that allow for entrepreneurial spin-offs efficiently promote invention within the firm. Financial contracts such as debt and convertible preferred securities are useful for financing independent inventors and startups that focus on R&D.

Delegation of R&D raises subtle and complex questions about experimental design and statistical inference. Although optimal statistical decisions are highly desirable, the incentives of firms that manage or sponsor R&D may not be perfectly aligned with those of researchers. Because it is costly and difficult to monitor scientific and technological research, it is necessary to rely on contractual incentives based on outcomes. Our analysis suggests that the study of contractual incentives for R&D can be extended address a wide range of problems encountered in conducting experiments, gathering data, and making statistical inferences. Experimental design affects incentives for personnel engaged in R&D; simultaneous search can lead to insufficient sampling and sequential search can lead to excessive sampling and delays. These incentive effects have consequences for R&D costs and the quality of innovation. Managers may choose to devote effort to monitoring R&D and developing other means of encouraging or directing R&D.

Investment in producing and marketing innovative products and establishing innovative production facilities may overshadow the considerable investment that companies make in R&D. The quality of inventions affects the performance of the firm's innovative activities. In turn, the effectiveness of delegated R&D depends on how the firm's innovative activities affect incentives for invention. Our results suggest that organizations should consider how best to manage interactions between specialized R&D activities and implementation of inventions through product and process innovation.

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