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Knowledge as Property Rights under the Ratchet Effect of Innovation*

Teck Yong Tan[†]

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Abstract

This paper studies how reduced oversight creates an incentive for process innovation. With incomplete contracts, tight monitoring of workers creates a ratchet effect of innovation. Under reduced oversight, a worker accrues private knowledge about his innovation, which serves as a substitute for its inalienable property rights. The resulting asymmetric information generates an information rent for the worker, which feeds back as an innovation incentive ex-ante. A weak early production incentive is required to complement it. Innovations are generally underutilized ex-post, and mildly successful innovations are not distinguished from failed innovation attempts.

Keywords: Ratchet effect, process innovation, asymmetric information, moral hazard

JEL Classification: D21, D86, O31

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[†]Nanyang Technological University. Email: teckyongtan@ntu.edu.sg.

1 Introduction

Freedom provision at the workplace is increasingly becoming an important element of successful management practices. Scholars from various fields have provided substantial empirical evidence suggesting that autonomy provision to individuals often leads to improved performances,¹ but most have attributed these positive effects to better flexibility and the workers’ intrinsic motivation derived from freedom provision. This paper considers a more subtle benefit from freedom provision, which is that having less oversight in a firm can also help incentivize process innovations from its workers.

Since the seminal work of [Aghion and Tirole \(1994\)](#), the difficulty in motivating innovation with incomplete contracts is well-recognized. For process innovations that improve basic functionality within a firm, the logic behind this difficulty is as follows: if a firm observes that its worker has uncovered a more efficient work method through his own innovative initiative, the firm will raise the worker’s future performance requirement. Anticipating such a ratchet effect of innovation, the worker never tries to innovate.

In this paper, I consider how reduced monitoring can help restore a worker’s incentive for process innovation. The logic follows from recognizing that the private knowledge of a process innovation is a substitute for its inalienable property rights. In particular, reduced oversight facilitates a worker to accrue private information about any useful discovery from his own innovative initiative. This private information allows the worker to generate an information rent from the firm, which acts as the innovation’s “royalty” and feeds back as the worker’s ex-ante incentive to innovate. However, the analog to a royalty payment is

¹For example, [Andrews and Farris \(1967\)](#) show that scientists are more likely to innovate under higher degree of freedom; [Amabile et al. \(1990\)](#) find that workers exhibit lower levels of creativity when being watched while working; [Shalley et al. \(2000\)](#) find that the autonomy to make decision increases employees’ commitment to the organization and fosters innovation; [Elloy \(2005\)](#) finds that employees in self-managed teams exhibit higher levels of organizational commitment; [Falk and Kosfeld \(2006\)](#) find experimental evidence that agents react negatively to actions deemed controlling by reducing performances; and [Bloom et al. \(2015\)](#) find that call center operators experience a 13% increase in overall performance when working from home.

not perfect because the resulting asymmetric information also leads to inefficiency in the use of the innovation ex-post. Therefore, incentivizing process innovations through freedom provision is not always profitable.

Although this logic is related to a principal’s gain from “strategic ignorance” under incomplete contracts, the mechanism here is quite different from most existing papers exhibiting this theme. Perhaps the best known of these papers in the literature is Crémer’s (1995) analysis of arm’s-length relationships giving credibility to a principal to follow through on ex-post punishments, thus strengthening the agent’s ex-ante effort incentives. Prat (2005), Crémer (2010) and Shin and Strausz (2014) also consider how committing not to monitor the agent’s actions can facilitate the elicitation of the agent’s private information. In contrast, in this paper, the principal gains from being able to credibly leave a rent to the agent later, which then improves incentives in the early period. Moreover, not many papers have studied the direct relationship between monitoring and innovation incentives, despite well-documented evidence linking the two factors.² In addition, the analysis here on the contracts required to complement the monitoring environment contributes to the understanding of some nuanced features pertaining to innovation incentives.

I consider a model in which a principal (she) interacts with an agent (he) for two periods. In each period, the agent chooses between producing a binary output with an old (o) or a new (n) technology. The probability of getting the high output with either technology is the agent’s effort, and the two technologies differ only in their effort costs. The cost efficiency of o is commonly known—technology o represents the “status quo” work method. On the other hand, the cost efficiency of n is unknown, but its value, which comes from a continuum, can

²The only known exceptions are Riordan (1990) and Kastl et al. (2013), but neither paper considers incentive contracts. Moreover, Riordan (1990) considers the decision to vertically integrate rather than the monitoring environment. Kastl et al. (2013) study how the delegation of decisions on ex-post efforts for output affects the workers’ incentives to engage in formal R&D activities, whereas this paper is about incentives for process innovation induced from allowing the workers to have private information about the innovation.

be perfectly learned by producing with n in period 1. This creates an option value for period 2: if n turns out to be more cost-efficient than o , the agent can continue to use n in period 2; otherwise, he can revert to using o . Therefore, using n in period 1 is an innovation attempt to uncover a more cost-efficient technology for the future. However, the common prior belief is that the expected cost efficiency of n is worse than o , so the cost of an innovation attempt is the use of a myopically less cost-efficient technology in period 1. The principal can only enforce spot contracts on the outputs and hence, she offers a bonus-wage contract at the start of each period. The key frictions in the model arise from the principal's inability to contract on the innovation and commit to long-term contracts.

I consider two types of monitoring environment. Under “*tight-monitoring*” (TM), when the agent produces with n , the principal also learns n 's cost efficiency together with the agent, which then creates a ratchet effect of innovation. When the principal observes that n is more cost-efficient than o and hence knows that the agent's effort cost has decreased, she decreases the compensation in the period-2 contract, thus extracting all the innovation surplus. Anticipating no gain in period 2, the agent always produces with o in period 1 since the expected effort cost is lower for o . Therefore, innovation is never possible under TM.

On the other hand, under a “*freedom-at-work*” (FW) environment, when the agent experiments with n in period 1, he *privately* learns its cost efficiency. With asymmetric information in period 2, the principal offers a menu of bonus-wage contracts to screen the agent. Since a better cost efficiency of n (i.e., a better innovation) implies a lower marginal cost of effort, the marginal cost of increasing the probability of getting the bonus is also lower. Therefore, an agent with a better innovation will accept a “riskier” contract with a lower base wage in exchange for a higher bonus. Thus, information revelation is induced with a bonus schedule that increases with the innovation quality, while the base wage schedule decreases with it.

The optimal menu also features contract pooling for an agent whose cost efficiency of n is worse than that of o (i.e., a failed innovation attempt) with agents whose cost efficiency of

n is only slightly better than that of o (i.e., mildly successful innovations). This is because all failed-innovator agents revert to using o in period 2, thus creating a mass point at the “type” with a cost efficiency of o . If the principal also wants to separate the mildly successful innovators from these failed innovators, she must lower the bonus of the contract meant for the failed-innovator type, but the resulting loss in surplus is very costly because the atomless distribution of any one type of successful innovator is incommensurate with the mass of the failed-innovator type. Therefore, the possibility of an innovation failure implies that innovations have to be sufficiently successful before they are recognized by the principal with increasingly powerful bonuses.

Under the menu of period-2 contracts, any agent with a successful innovation gets an information rent. Although the potential for this rent creates an incentive for the agent to experiment with n in period 1, the principal must also complement it with a sufficiently low period-1 bonus. This is because under any period-1 bonus, the expected marginal effort cost of n is higher than that of o ; hence, the agent’s optimal period-1 effort on o is always higher than that on n . Therefore, a high period-1 bonus encourages the agent to use o , which increases his chances of getting the period-1 bonus, at the expense of forgoing the potential period-2 rent, which comes from experimenting on n .

To highlight the agency costs of innovation, I also consider how the ex-ante distribution of the cost efficiency of n affects the principal’s payoffs from motivating the agent to innovate. Intuitively, when the distribution becomes more concentrated at better cost efficiency levels, the expected innovation surplus is higher, and the ex-ante cost of experimenting with n is also lower. However, the innovation incentive here is created by an information rent from asymmetric information, which results in inefficiency in the use of the innovations ex-post. The amount of this inefficiency is affected by the distribution of the potential innovation—a better distribution can worsen this inefficiency and/or make it more difficult to induce asymmetric information. I provide a particular parametrization in which an improvement

(appropriately defined) in the distribution unambiguously increases the principal’s expected payoffs from motivating the agent to innovate. Since the principal’s expected payoff under TM is unaffected by the distribution of the cost efficiency of n , this also suggests when the FW environment is more likely to be preferred over TM.

The rest of the paper proceeds as follows. Section 2 discusses the related literature, and Section 3 describes the model. Next, Sections 4 and 5 study the contracting problem under the TM and FW environments, respectively. Section 6 considers the comparative statics, and Section 7 concludes.

2 Related Literature

Freixas et al. (1985), Lazear (1986), Gibbons (1987), Laffont and Tirole (1987, 1988) and Kanemoto and MacLeod (1992) are some early contributions on the ratchet effect that show that an agent rationally restricts output to prevent his future performance requirement from ratcheting up. By contrast, the ratchet effect in this paper concerns the worker not choosing the principal’s desired technology instead of output restriction. More substantially, the ratchet effect literature typically assumes that the agent has ex-ante private information and studies the principal’s problem arising from short-term contracting; by contrast, information is ex-ante symmetric here. Two notable exceptions are Bhaskar (2014) and Bhaskar and Mailath (2019), who study the ratchet effect under ex-ante symmetric uncertainty. However, the ratchet effect in these two papers arises from the agent shirking and gaining rent from the principal holding wrong—in particular, more pessimistic—beliefs about the underlying state. Moreover, while the principal suffers from the agent’s ability to create differential beliefs there, the principal can benefit here from the agent having private information.

This paper also relates to the literature on experimentation. Bergemann and Hege (1998, 2005), Hörner and Samuelson (2013), and Halac et al. (2016) (among others) study optimal

contracting under moral hazard in the agent’s experimentation effort; [Gomes et al. \(2016\)](#), [Guo \(2016\)](#) and [Halac et al. \(2016\)](#) allow the agent to have private information about the experimentation returns. The way the tension between experimentation and forgoing current productivity is incorporated here is similar to [Manso \(2011\)](#), who emphasizes the importance of commitment to long-term contracts to motivate innovation. Distinguishing from this literature, these papers focus on hard incentives from contracts and stopping policies and study how they affect the agent’s dynamic incentives for experimentation. In contrast, the study here considers an incomplete contracting environment and uses commitment to not monitor to generate experimentation incentives.

Next, the agent’s experimentation in this paper can be viewed as an investment in a hold-up problem, and the literature has noted that asymmetric information about the investment can potentially protect the investing party from being held up, thus restoring ex-ante investment incentives. [Gul \(2001\)](#), [González \(2004\)](#), [Lau \(2008\)](#), [Hermalin \(2013\)](#) and [Nguyen and Tan \(2019\)](#) make this point by studying deterministic investments; by contrast, the “investment” here is stochastic. [Hermalin and Katz \(2009\)](#) and [Halac \(2015\)](#) consider stochastic investments, but their models have no room for screening and have a different focus.³ More substantially, this paper is not concerned with the intensive margin on the investment, but it embeds a moral hazard problem in production at the investment stage. In turn, a key focus in this paper is also on the incentive contract, which must be appropriately designed to generate asymmetric information.

Finally, a few papers (e.g., [Crémer and Khalil \(1992\)](#), [Lewis and Sappington \(1997\)](#), [Crémer et al. \(1998a,b\)](#), [Szalay \(2009\)](#) and [Iossa and Martimort \(2015\)](#)) have studied the contracting problem involving both screening and incentivizing the agent to acquire private

³Only [González \(2004\)](#) has screening among these papers after the agent plays a mixed strategy regarding the deterministic investment. Relatedly, but with a different focus, [Condorelli and Szentes \(2019\)](#) study how the agent would choose the distribution of his private information before the contracting stage to maximize his rent.

information. The dual objectives are accomplished by the same set of contracts in these papers. In contrast, since the menu of contracts in my model is offered only after the information acquisition process in period 1, the agent's information acquisition incentive is derived separately by the monitoring environment and the period-1 contract.

3 Model

Consider a two-period principal-agent model. To abstract from other frictions, I assume that both parties are risk neutral, do not discount the future, have no limited liability and have zero per-period outside options. In each period, the agent can exert effort on one of two available technologies $\tau \in \{o, n\}$, and he can use a different technology across the two periods. The two technologies have the same productivity. Each technology generates a stochastic per-period revenue of $y \in \{0, Y\}$ for the principal, where $Y > 0$, and the probability of getting Y is the agent's effort, which is chosen from the continuum $[0, 1]$. To save on time subscript, the agent's period-1 effort is denoted by e , and his period-2 effort is denoted by its Greek letter counterpart ε .

The cost of effort depends on the technology. An effort e (respectively, ε) exerted on technology τ incurs a cost of $\psi(e/\theta^\tau)$ (respectively, $\psi(\varepsilon/\theta^\tau)$) to the agent, where the cost function ψ satisfies Assumption 1 below. $\theta^\tau \in (0, 1]$ is the cost efficiency of technology τ and it is constant across periods; a higher value of θ^τ indicates a more cost-efficient technology.

Assumption 1. $\psi(x) = \infty$ for all $x \geq 1$. For all $x \in [0, 1)$, $\psi(x)$ is continuously differentiable, strictly increasing and strictly convex, with $\psi(0) = \psi'(0) = 0$, $\lim_{x \uparrow 1} \psi(x) = \infty$ and $0 \leq \psi'''(x) \leq 2(\psi''(x))^2/\psi'(x)$.⁴

⁴The Inada condition on ψ ensures that the agent's optimal effort choice is always interior. The bounds on the third derivative of ψ is a technical condition that ensures that the marginal effect of incentives on the agent's optimal effort choice is increasing in θ^τ . Examples of functions that satisfy Assumption 1 for the domain of $x \in [0, 1)$ include $\psi(x) = -\log(1-x) - x$, and $\psi(x) = x^{m_2}/(1-x)^{m_1}$ with $m_1 \geq 1$ and $m_2 > m_1$.

In terms of information, θ^o is commonly known. On the other hand, θ^n is ex-ante unknown to both the players, and their common prior on θ^n is represented by a distribution function F on $[\underline{\theta}, \bar{\theta}]$, with $0 < \underline{\theta} < \bar{\theta} \leq 1$. If n is used in period 1 with $e > 0$, the value of θ^n is learned at the end of period 1. Therefore, using n in period 1 is interpreted as an innovation attempt to uncover a possibly more cost-efficient technology.

Assumption 2. *F has an atom-less density f that is differentiable and strictly positive in its support. Moreover $E[\theta^n] \leq \theta^o < \bar{\theta}$, and $\frac{d}{d\theta^n} \left(\frac{1-F(\theta^n)}{f(\theta^n)} \right) \leq 0$.*⁵

Following [March \(1991\)](#), the use of the known technology o in period 1 is termed *exploitation*, while the use of the technology with an unknown efficiency (i.e., n) is termed *exploration*. Together with the convexity of ψ , the assumption that $E[\theta^n] \leq \theta^o$ implies that o is ex-ante more cost-efficient than n ,⁶ thus reflecting that it tends to be more costly to engage in an innovative activity. However, exploration might lead to uncovering of a more efficient technology, which is beneficial for future production.

3.1 Contracts

The revenue y is the only contractible term throughout. Since it is often difficult to observe or verify effort, the agent's effort is assumed to be non-contractible. τ is also not contractible because n represents an innovation attempt, which tends to be difficult to identify and describe ex-ante—innovative activities typically involve coming up with new ideas or exploring previously untested approaches, both of which often end up with no tangible outcomes. Therefore, it is difficult to distinguish between a worker carrying out an honest experimentation from a shirking worker. In the same vein, the experimentation outcome θ^n

⁵The non-increasing inverse hazard rate property is a standard assumption in the screening literature that ensures that the screening problem is well-behaved. However, as shown later, the screening problem here will still exhibit “bunching,” despite this assumption.

⁶By Jensen's inequality, $E[\psi(e/\theta^n)] > \psi(e/E[\theta^n]) \geq \psi(e/\theta^o) \forall e$.

is also assumed to be non-contractible because of the difficulties in describing the innovation before it is realized and also in verifying the value of an innovation by a third party.⁷

The principal also cannot enforce any long-term contract. Therefore, at the start of each period, the principal offers the agent a take-it-or-leave-it contract that specifies a fixed transfer and a bonus for output Y . Like the notation for effort, the period-1 contract terms are denoted by Roman alphabets and the period-2 contract terms by their Greek letter counterparts. Therefore, the contracts are (a, b) and (α, β) for periods 1 and 2, respectively, where a and α are the fixed wages and b and β are the bonuses. Henceforth, whenever unspecified, all the payoffs refer to expected payoffs, and negative payments are transfers from the agent to the principal.

3.2 Monitoring environments

I consider the principal's problem under two types of monitoring environment—*tight-monitoring* (TM) and *freedom-at-work* (FW). In both the environments, y is publicly observed and contractible, while the agent's effort is his private information.

Under TM , the principal also observes the agent's technology choice τ and learns the value of θ^n together with the agent if the agent uses n in period 1. For example, firms can install surveillance cameras and time monitoring systems to observe if any worker is trying out new work methods and the time efficiency of these new methods; managers of delivery drivers can install location tracking devices in the vehicles to monitor the efficiency of any new delivery routine or route experimented with by their drivers.

⁷Holmström (1989) provides an excellent discussion of why innovation attempts are often difficult-to-measure activities, citing reasons that innovation projects are often multi-staged and unpredictable, and it is often not clear ex-ante what the correct course of action is. Aghion and Tirole (1994) also argue that innovations are always unpredictable and hence difficult to contract on before they are realized. Moreover, innovations are often so complex that even if the parties can agree on the innovation ex-ante, courts can still lack the requisite technical knowledge to enforce the contract; some innovations might also take a long time for their full value to be realized, so it is impossible to have an agreement on the immediate value for contracting purposes.

On the other hand, under FW, the principal never observes τ nor θ^n . This implies that if the agent uses n in period 1, the value of θ^n is *privately* learned by the agent at the end of period 1, which then results in asymmetric information in period 2. As noted in fn. 14, the main driving force behind the results is the difference in the observability of θ^n in the two environments.⁸⁹

3.3 First best benchmark

Let $S(x) := \max_{\varepsilon} \{\varepsilon Y - \psi(\varepsilon/x)\}$ be the first best current period social surplus when the agent has a known cost efficiency of x . When engaging in exploitation, θ^n remains unknown in period 2, so o is the more cost-efficient technology in period 2. Therefore, the first best total social surplus from exploitation is $S^{exploit} := 2S(\theta^o)$. On the other hand, the first best total social surplus from exploration is

$$S^{explore} := \max_e \left\{ eY - E \left[\psi \left(\frac{e}{\theta^n} \right) \right] \right\} + F(\theta^o) S(\theta^o) + (1 - F(\theta^o)) E[S(\theta^n) | \theta^n \geq \theta^o].$$

Assumption 3. $S^{explore} > S^{exploit}$. Therefore, exploration is socially efficient in the absence of other frictions.

Assumption 3 is equivalent to the following condition:

$$(1 - F(\theta^o)) (E[S(\theta^n) | \theta^n \geq \theta^o] - S(\theta^o)) > S(\theta^o) - \max_e \left\{ eY - E \left[\psi \left(\frac{e}{\theta^n} \right) \right] \right\}. \quad (1)$$

The left-hand side is the expected option value in period 2 derived from choosing n in period 1, while the right-hand side is the expected period-1 loss from experimenting on n .

⁸This implies that we can also model more general forms of monitoring environment by letting the principal observe θ^n with only some probability or letting her observe an imperfect signal about θ^n .

⁹The principal's ability to commit to the type of monitoring environment can come from the high cost of installing and implementing (or removing) monitoring facilities. Moreover, aspects such as the firm's culture and the workplace arrangement are not easily changed, and these aspects are directly related to the monitoring environment in the firm.

Lemma 1. *If the principal can commit to long-term contracts on revenues y , she can achieve the first best social surplus $S^{explore}$ as her total payoff under both TM and FW.*

Proof. Offer period-1 contract $(a, b) = (-S^{explore}, Y)$ and period-2 contract $(\alpha, \beta) = (0, Y)$.

□

With long-term commitment, the principal can commit ex-ante to make the agent the residual claimant of the surplus in *both* periods, thus providing first best incentives for both the effort and the technology choices to the agent. Since the agent has unlimited liability, the principal can extract the first best surplus via the fixed transfer in period 1. Note that if the principal can only enforce spot contracts, then offering the long-term contracts in Lemma 1 as the sequence of spot contracts is not an equilibrium under both monitoring environments. This is because the period-2 contract $(\alpha, \beta) = (0, Y)$ always leaves an expected rent to the agent, so the principal can improve her payoff by charging a negative fixed wage in period 2 to extract the rent. Anticipating this, the agent will not accept the period-1 contract, which has a high fixed transfer of $S^{explore}$ to the principal. Lemma 1 thus illustrates how the principal's inability to commit to long-term contracts plays a crucial role in generating the frictions in the model that are studied in the next two sections.¹⁰

4 Tight-Monitoring (TM)

This section studies the TM environment. Since information is always symmetric in period 2, the principal can efficiently “sell the period-2 firm to the agent.” Anticipating that his period-2 payoff is always zero, the agent myopically maximizes only his period-1 payoff at

¹⁰Lemma 1 also relies on the agent having sufficiently “deep pockets.” This unlimited liability assumption, while arguably not very realistic for workers, allows us to isolate the frictions due to ex-ante incomplete contracting along both the time dimension and innovations. The subsequent trade-offs in the model will still arise if the agent has limited liability, but the analysis is significantly more muddled due to the rents that the agent inherently accrues from having limited liability.

the start of period 1. Consider a period-1 bonus b and let e^n be the agent's optimal period-1 effort on n (which is dependent on b). Since

$$e^n b - E \left[\psi \left(\frac{e^n}{\theta^n} \right) \right] < e^n b - \psi \left(\frac{e^n}{E[\theta^n]} \right) \leq e^n b - \psi \left(\frac{e^n}{\theta^o} \right) \leq \max_e \left\{ e b - \psi \left(\frac{e}{\theta^o} \right) \right\}, \quad (2)$$

the agent uses o in period 1. This illustrates the ratchet effect of innovation: when the employer cannot commit to not expropriating all the efficiency gains, the worker responds by not trying to improve efficiency.

Proposition 1. *Under TM, there is a unique subgame perfect equilibrium. Along the equilibrium path, the optimal contracts are time-stationary, with $(a^{TM}, b^{TM}) = (b^{TM}, \beta^{TM}) = (-S(\theta^o), Y)$. The agent uses o every period, and the principal's total payoff is $S^{exploit}$.*

Remark 1. The ratchet effect remains when the agent's effort is also observable and contractible. To see this, suppose that the principal can enforce effort-contingent payments, but the technology that the agent uses to fulfill the effort obligation remains uncontractible. In period 2, since information is symmetric, the principal will enforce the agent to exert the first best effort (conditional on the available information in period 2) and exactly compensates his effort cost based on his more cost-efficient technology. Therefore, the agent's period-2 payoff is always zero. Anticipating this, the agent always chooses to fulfill his period-1 effort obligation with the more cost-efficient technology o .

5 Freedom-at-Work (FW)

This section studies the FW environment. Subsection 5.1 considers the principal's optimal contract that motivates the agent to engage in exploration with some positive probability, and Subsection 5.2 considers the optimal contract that motivates only exploitation.

5.1 Optimal contract with exploration

Fix a $\lambda \in (0, 1]$ and let it denote the probability that the agent chooses n in period 1. The analysis begins at period 2 (in Subsection 5.1.1) when the principal has the correct conjecture about λ , and the agent can possibly have private information about θ^n . Therefore, the principal screens the agent with a menu of contracts. Note that since the agent's period-1 effort is chosen *before* he learns the value of θ^n (if he chooses n), the realization of y in period 1 does not carry any information on the agent's period-1 technology choice or the value of θ^n . Thus, the principal's period-2 menu is independent of the period-1 realization of y . In equilibrium, the agent correctly anticipates this period-2 menu, which affects his incentive to choose n or o in period 1. The optimal period-1 contract that motivates the agent to choose n with probability λ in period 1 is then solved in Subsection 5.1.2, while taking into account these incentives.

5.1.1 Period 2

In period 2, the agent's payoff-relevant information is the cost efficiency of his more efficient technology. If he had used n in period 1, his period-2 cost efficiency is $\max\{\theta^n, \theta^o\}$; if he had used o in period 1, by the argument in (2), his period-2 cost efficiency is θ^o . Therefore, the agent's private type in period 2 is denoted by $\theta \in [\theta^o, \bar{\theta}]$, and its distribution, which represents the principal's belief about θ , is F^λ , where for any $x \in [\theta^o, \bar{\theta}]$,

$$F^\lambda(x) := \Pr(\theta \leq x) = 1 - \lambda + \lambda \left(F(\theta^o) + \int_{\theta^o}^x f(t) dt \right). \quad (3)$$

Type θ^o is an agent who did not try to innovate or has failed in his innovation attempt in period 1, and θ^o has a probability mass of $F^\lambda(\theta^o) = 1 - \lambda + \lambda F(\theta^o)$. A successful innovator has a type $\theta > \theta^o$, and a higher type is interpreted as an agent with a better innovation.

After accepting a period-2 contract (α, β) , the optimal effort choice problem of type θ is

$\max_{\varepsilon} \{\alpha + \varepsilon\beta - \psi(\varepsilon/\theta)\}$. Let $\varepsilon(\beta, \theta)$ be its solution, which is implicitly characterized by the first-order condition

$$\beta = \frac{1}{\theta} \psi' \left(\frac{\varepsilon(\beta, \theta)}{\theta} \right). \quad (4)$$

By the revelation principle, it suffices to consider only truth-telling direct mechanisms with the obedience constraint in (4). This is equivalent to considering the agent's indirect utility.

Let

$$u(\beta, \theta) := \max_{\varepsilon} \left\{ \varepsilon\beta - \psi \left(\frac{\varepsilon}{\theta} \right) \right\} = \varepsilon(\beta, \theta)\beta - \psi \left(\frac{\varepsilon(\beta, \theta)}{\theta} \right). \quad (5)$$

The agent's indirect utility under a contract (α, β) is $\alpha + u(\beta, \theta)$, and its properties are stated in Lemma 2. Henceforth, subscript i denotes the partial derivative with respect to argument i .

Lemma 2. *Both $\varepsilon(\beta, \theta)$ and $u(\beta, \theta)$ are continuously differentiable and strictly increasing in both of their arguments. $\varepsilon(\beta, \theta)$ is strictly concave in β and strictly convex in θ . $u(\beta, \theta)$ is strictly convex in both of its arguments. The agent's indirect utility satisfies the single-crossing condition: $u_{\theta\beta}(\beta, \theta) > 0 \forall \beta > 0$.*

Next, consider a menu of contracts denoted by $\{\alpha(\theta), \beta(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$,¹¹ and let $\bar{U}(\theta) = \alpha(\theta) + u(\beta(\theta), \theta)$. The menu is feasible if

$$\bar{U}(\theta) \geq 0, \quad \forall \theta \in [\theta^o, \bar{\theta}]; \quad (\text{IR})$$

$$\bar{U}(\theta) \geq \alpha(\theta') + u(\beta(\theta'), \theta), \quad \forall \theta', \theta \in [\theta^o, \bar{\theta}]. \quad (\text{IC})$$

Condition (IR) is the agent's participation constraint, and condition (IC) is his truth-telling

¹¹The convexity of $u(\beta, \theta)$ in β is non-standard relative to textbook treatments of screening problems (e.g., chapter 7 of Fudenberg and Tirole (1991)). This convexity leaves open the possibility that the principal might benefit from offering stochastic bonuses to the agent. However, this turns out not to be the case under optimality (see fn. 24). For ease of exposition, I restrict attention to only deterministic contracts but note that doing so is without loss of generality.

constraint. The problem of the principal in period 2 is thus program $(\mathcal{P})$:

$$\max_{\alpha(\cdot), \beta(\cdot)} \int_{\theta^o}^{\bar{\theta}} \left(\varepsilon(\beta(\theta), \theta) [Y - \beta(\theta)] - \alpha(\theta) \right) dF^\lambda(\theta) \quad \text{subject to (IR), (IC)}. \quad (\mathcal{P})$$

Lemma 3. *A menu of contracts $\{\alpha(\theta), \beta(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$ satisfies constraint (IC) if and only if for all $\theta \in [\theta^o, \bar{\theta}]$, the following two conditions are satisfied:*

1. $\bar{U}(\theta) = \bar{U}(\theta^o) + \int_{\theta^o}^{\theta} u_\theta(\beta(t), t) dt.$
2. $\beta(\theta)$ is non-decreasing.

Lemma 3.1 implies that $\bar{U}(\theta^o) = 0$ under the optimal menu. Substituting in $\alpha(\theta)$ by $\alpha(\theta) = \bar{U}(\theta) - u(\beta(\theta), \theta)$ and Lemma 3.1, and after some rearrangement, program $(\mathcal{P})$ can be reformulated as program $(\mathcal{P}')$:

$$\max_{\beta(\cdot) \in \mathcal{B}} \int_{\theta^o}^{\bar{\theta}} v(\beta(\cdot), \theta) dF^\lambda(\theta), \quad (\mathcal{P}')$$

where $\mathcal{B}$ is the set of non-decreasing functions with domain $[\theta^o, \bar{\theta}]$, and

$$v(\beta(\cdot), \theta) := \underbrace{\varepsilon(\beta(\theta), \theta) Y - \psi\left(\frac{\varepsilon(\beta(\theta), \theta)}{\theta}\right)}_{s(\beta(\theta), \theta)} - \underbrace{\int_{\theta^o}^{\theta} u_\theta(\beta(t), t) dt}_{r(\beta(\cdot), \theta)}. \quad (6)$$

$v(\beta(\cdot), \theta)$ is the principal's period-2 payoff from type θ under a bonus schedule $\beta(\cdot)$. It consists of the social surplus $s(\beta(\theta), \theta)$ less the agent's information rent $r(\beta(\cdot), \theta)$. Doing integration by parts, the objective in $(\mathcal{P}')$ becomes

$$\max_{\beta(\cdot) \in \mathcal{B}} \lambda \int_{\theta^o}^{\bar{\theta}} \phi(\beta(\theta), \theta) f(\theta) d\theta + s(\beta(\theta^o), \theta^o) F^\lambda(\theta^o), \quad (7)$$

where $\phi(\beta, \theta) := s(\beta, \theta) - u_\theta(\beta, \theta) H(\theta)$, and $H(\theta) := (1 - F(\theta)) / f(\theta)$. ϕ is typically called the *virtual surplus* in the screening literature. Here, the term $\lambda \int_{\theta^o}^{\bar{\theta}} \phi(\beta(\theta), \theta) f(\theta) d\theta$

is the principal's expected period-2 payoff from the successful innovators, while the term $s(\beta(\theta^o), \theta^o) F^\lambda(\theta^o)$ is the expected period-2 payoff from the failed innovators.¹²

Proposition 2. *The solution to program $(\mathcal{P})$ is $\{\alpha^\lambda(\theta), \beta^\lambda(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$:*

$$\beta^\lambda(\theta) = \begin{cases} \hat{\beta}(\theta) & , \forall \theta \in [T^\lambda, \bar{\theta}] \\ \hat{\beta}(T^\lambda) & , \forall \theta \in [\theta^o, T^\lambda] \end{cases}, \quad (8)$$

where $\hat{\beta}(\cdot)$ is uniquely characterized by

$$s_\beta(\hat{\beta}(\theta), \theta) = \varepsilon_\theta(\hat{\beta}(\theta), \theta) H(\theta), \quad \forall \theta \in [\theta^o, \bar{\theta}], \quad (9)$$

and T^λ is uniquely characterized by

$$\lambda \int_{\theta^o}^{T^\lambda} \phi_\beta(\hat{\beta}(T^\lambda), \theta) f(\theta) d\theta + s_\beta(\hat{\beta}(T^\lambda), \theta^o) F^\lambda(\theta^o) = 0; \quad (10)$$

and

$$\alpha^\lambda(\theta) = \begin{cases} \int_{\theta^o}^{\theta} u_\theta(\beta^\lambda(t), t) dt - u(\beta^\lambda(\theta), \theta) & , \forall \theta \in [T^\lambda, \bar{\theta}] \\ -u(\hat{\beta}(T^\lambda), \theta^o) & , \forall \theta \in [\theta^o, T^\lambda] \end{cases}. \quad (11)$$

¹²The mass point at θ^o violates the non-increasing inverse hazard rate property. This implies that the standard procedure of “optimizing point-wise” for program $\mathcal{P}'$ in (7) does not give a monotonic bonus schedule. When this happens, the literature typically uses some form of control theoretic techniques to solve the screening problem. However, the mass point at type θ^o precludes a direct application of optimal control theory. Hellwig (2010) provides a technique to handle screening problems with mass points in the support. The basic idea there is to develop a “pseudo-type” $\tilde{\theta}$ of the original type θ , where the distribution of $\tilde{\theta}$ has no mass point. Non-smooth analysis techniques in optimal control theory can then be applied on the “pseudo” problem, and Hellwig proves that the solution to the “pseudo” problem is also the solution to the original problem. The “bunching” of contracts for the mass point type θ^o with types slightly higher than θ^o , as shown in Proposition 2, is a general phenomenon, which is proved in Theorem 2.3 in Hellwig (2010). However, because the problem here is more specific (in particular, the mass point exists only at the lowest type of the support) than the one considered by Hellwig, the optimal bonus schedule can be solved here via a more straightforward method. This method is more in line with developing the intuition behind the optimal menu here, and it also circumvents the use of optimal control theory techniques, which implies that there is no need to *a priori* assume that the optimal bonus schedule is differentiable.

For all $\lambda \in (0, 1]$:

- $\beta^\lambda(\cdot)$ is continuous and strictly increasing for $\theta > T^\lambda$, with $\beta^\lambda(\bar{\theta}) = Y$.
- $\alpha^\lambda(\cdot)$ is continuous and strictly decreasing for $\theta > T^\lambda$.
- $T^\lambda \in (\theta^o, \bar{\theta})$, and T^λ is strictly decreasing in λ .
- The value of program $(\mathcal{P})$ (i.e., the principal's payoff in period 2) is strictly increasing in λ .

Figure 1: Optimal period-2 bonus schedule $\beta^\lambda(\cdot)$

The dotted graph represents $\hat{\beta}(\cdot)$. The solid graph represents the optimal bonus schedule $\beta^\lambda(\cdot)$; the schedule is flat for $\theta \in [\theta^o, T^\lambda]$ and strictly increasing for $\theta > T^\lambda$.

Figure 1 illustrates $\beta^\lambda(\cdot)$. To see why the optimal bonus schedule is increasing while the fixed wage schedule is decreasing, first recall that the agent's optimal effort is positively

correlated with his type. Since a lower type has a lower probability of getting the bonus, the principal has to compensate him with a higher fixed wage to satisfy his participation constraint, which then creates an incentive for the agent to under-report his type. To counter this, the principal decreases the bonus for lower types to make their contracts less attractive to the higher types, thus decreasing the information rent to the high-type agents. However, a lower bonus also decreases the surplus generated. Therefore, the principal faces a trade-off between efficient surplus production and information rent minimization.

This trade-off is reflected in equation (9). The term $s_\beta(\hat{\beta}(\theta), \theta)$ is the marginal gain in surplus from type θ when his bonus is increased, while the term $\varepsilon_\theta(\hat{\beta}(\theta), \theta) H(\theta)$ is the resulting marginal increase in (virtual) information rent provision. Such a trade-off results in inefficiency everywhere other than at the highest type.¹³

However, the trade-off in equation (9) is a local trade-off, which is not valid at θ^o . This is because the type just above θ^o is of measure zero and is hence incommensurate with the mass point at θ^o . Instead, the principal must pool some types that are above θ^o to do this trade-off, thus creating a “bunching” region, and this region is optimally determined in equation (10). The term $s_\beta(\hat{\beta}(T^\lambda), \theta^o) F^\lambda(\theta^o)$ represents the marginal increase in surplus generated by θ^o when his bonus is increased, and this surplus is significant due to the mass of $F^\lambda(\theta^o)$. On the other hand, the term $\lambda \int_{\theta^o}^{T^\lambda} \phi_\beta(\hat{\beta}(T^\lambda), \theta) f(\theta) d\theta$ represents the marginal increase in the information rent to the higher types when the bonus for θ^o is increased.

Contract pooling at the low types implies that only sufficiently successful innovations $\theta \in (T^\lambda, \bar{\theta}]$ are recognized and distinguished with increasingly powerful incentive contracts; on the other hand, the mildly successful innovations $\theta \in (\theta^o, T^\lambda]$ are treated as if their innovations are failures. Moreover, since T^λ is decreasing in λ , it implies that when the principal expects the agent to have engaged in exploration in period 1 with a lower probability, the threshold for recognition increases.

¹³The first best incentive for any θ is $\beta = Y$ because this induces the first best effort level.

Finally, the principal's payoff in period 2 is increasing in the probability of exploration, λ . Although this is intuitive, this result is less straightforward because a higher λ also increases the agency cost of innovation in period 2. To illustrate this agency cost, note that the social surplus generated from an innovation θ is $s(\beta^\lambda(\theta), \theta)$ under the optimal menu of contracts. On the other hand, if there is not any possibility of innovation, the agent's cost efficiency remains at θ^o , but the absence of asymmetric information would allow the principal to achieve the first best surplus under θ^o (i.e., $s(Y, \theta^o)$). Therefore, I define the innovation surplus of θ as $Innov^\lambda(\theta) := s(\beta^\lambda(\theta), \theta) - s(Y, \theta^o)$.

Lemma 4. *For all $\lambda \in (0, 1]$, $Innov^\lambda(\cdot)$ is continuous and strictly increasing, with $Innov^\lambda(\theta^o) < 0$ and $E[Innov^\lambda(\theta)] > 0$. For all $\theta \in (\theta^o, \bar{\theta})$, $\lambda < \lambda'$ implies that $Innov^\lambda(\theta) \geq Innov^{\lambda'}(\theta)$, with the inequality holding strictly when $\theta < T^\lambda$.*

For all $\lambda > 0$, $E[Innov^\lambda(\theta)] > 0$, which implies that innovation is ex-ante socially beneficial in expectation even in the presence of the agency costs. However, an innovation failure is always costly (i.e., $Innov^\lambda(\theta^o) < 0$), and this does not include the cost of using the ex-ante inferior technology n in period 1. Moreover, since $Innov^\lambda(\theta)$ is negative when θ is only slightly above θ^o , this implies that an innovation is socially beneficial ex-post *only* if it is sufficiently successful.

Next, a lower λ implies “less” asymmetric information in the sense that the principal knows there is a higher chance that the type is precisely θ^o . Therefore, there is less distortion in the effort incentives, resulting in $Innov^\lambda$ decreasing point-wise in λ . However, while a higher λ leads to a less efficient use of each innovation, the principal's payoff still increases with λ —as stated in the last part of Proposition 2—because the positive effect from a higher probability of getting an innovation dominates.

Before moving to period 1, I summarize the agent's period-2 payoff here:

Lemma 5. *Under $\{\alpha^\lambda(\theta), \beta^\lambda(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$ in period 2, if the agent uses n in period 1, his*

expected period-2 payoff is R^λ , where

$$R^\lambda = E[\bar{U}(\theta)] = \int_{\theta^o}^{\bar{\theta}} \left(\int_{\theta^o}^{\theta} u_\theta(\beta^\lambda(t), t) dt \right) dF(\theta) > 0. \quad (12)$$

If the agent uses o in period 1, his expected period-2 payoff is 0.

5.1.2 Period 1

Next, I consider the agent's incentives in period 1, taking into account that he anticipates receiving the menu $\{\alpha^\lambda(\theta), \beta^\lambda(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$ in period 2. Let

$$W^n(e, b) := eb - E\left[\psi\left(\frac{e}{\theta^n}\right)\right], \quad \text{and} \quad W^o(e, b) := eb - \psi\left(\frac{e}{\theta^o}\right).$$

Under a period-1 contract (a, b) , the agent's total (i.e., for both periods) payoff from using n (respectively, o) in period 1 with an effort e is $a + W^n(e, b) + R^\lambda$ (respectively, $a + W^o(e, b)$). Let $\bar{W}^\tau(b) := \max_e W^\tau(e, b)$ and $e^\tau(b) := \arg \max_e W^\tau(e, b)$ for $\tau \in \{o, n\}$.

Lemma 6. *$e^\tau(\cdot)$ is strictly increasing for $\tau \in \{o, n\}$, and $e^o(b) > e^n(b) \forall b > 0$. For each $\lambda \in (0, 1]$, there exists a unique bonus threshold $\bar{b}(\lambda) > 0$ such that $\bar{W}^n(b) + R^\lambda \geq \bar{W}^o(b)$ if and only if $b \leq \bar{b}(\lambda)$. For any $\lambda', \lambda \in (0, 1]$, $\lambda' > \lambda$, implies that $\bar{b}(\lambda') < \bar{b}(\lambda)$.*

The first property of $e^\tau(\cdot)$ is intuitive: a higher bonus induces a higher effort. Moreover, since o is ex-ante more cost-efficient than n in expectation, given any bonus, the agent chooses a higher effort when using o than when using n . Next, the comparison between the agent's total payoffs from using n and o in period 1 rests on the trade-off in payoffs across the two periods. $R^\lambda > 0$ implies that using n in period 1 provides an additional period-2 rent for the agent, whereas using o increases his probability of getting the period-1 bonus because of $e^o(b) > e^n(b)$. Therefore, if the period-1 bonus is too high, the agent's total payoff from using o in period 1 is higher than that from using n .

To motivate the agent to use n with probability $\lambda \in (0, 1]$ in period 1, the period-1 contract (a, b) must thus satisfy the following conditions:

$$a + \bar{W}^n(b) + R^\lambda \geq 0 \quad (13)$$

$$\text{if } \lambda \in (0, 1), \quad \bar{W}^n(b) + R^\lambda = \bar{W}^o(b) \quad (14)$$

$$\text{if } \lambda = 1, \quad \bar{W}^n(b) + R^1 \geq \bar{W}^o(b) \quad (15)$$

Condition (13) is the agent's participation constraint. Condition (14) implies that the agent is indifferent between using n and o in period 1, so he is willing to randomize between the two; condition (15) implies that the agent weakly prefers n to o .

Proposition 3. *Under FW, the optimal period-1 contract that motivates exploration with probability $\lambda \in (0, 1]$ is unique:*

- For $\lambda \in (0, 1)$, $b^\lambda = \bar{b}(\lambda)$, and $a^\lambda = -(\bar{W}^n(b^\lambda) + R^\lambda)$.
- For $\lambda = 1$, $b^\lambda = \min\{Y, \bar{b}(1)\}$, and $a^\lambda = -(\bar{W}^n(b^\lambda) + R^1)$.

$\lambda' > \lambda$ implies that $b^{\lambda'} < b^\lambda$.

For $\lambda \in (0, 1)$, condition (14) pins down the period-1 bonus, and the period-1 fixed wage is then set to extract all the agent's rent. For $\lambda = 1$, the contract needs to only make the agent weakly prefer n to o in period 1; by verifying that the principal's period-1 payoff is concave in b and maximized at Y , the optimal bonus is thus the minimum of Y and the bonus threshold.¹⁴ The bonus b^λ decreases with λ because when λ is low, innovations become rare

¹⁴For $\lambda = 1$, the outcome remains the same when the principal can observe the agent's choice of τ but cannot contract on it. The only difference is that when the agent chooses o in period 1 (i.e., a deviation), the principal knows about it. Instead of still offering the menu of contracts $\{\alpha^1(\theta), \beta^1(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$ in period 2, the principal offers the contract $\beta = Y$ and $\alpha = -s(Y, \theta^o)$, but this still gives the agent a zero period-2 payoff; therefore, the agent's period-1 incentives remain unchanged. For $\lambda \in (0, 1)$, things become different because the principal's actions in period 2 are as just described—she offers $\{\alpha^1(\theta), \beta^1(\theta)\}_{\theta \in [\theta^o, \bar{\theta}]}$ after observing $\tau = n$ in period 1 and offers $\beta = Y$ and $\alpha = -s(Y, \theta^o)$ after observing $\tau = o$. This implies that the agent's expected period-2 rent from choosing n in period 1 is always R^1 . Therefore, to induce $\lambda \in (0, 1)$, the period-1 bonus must be set to $\bar{b}(1)$ to maintain the agent's indifference between the two technologies.

in period 2, so the agent's information rent conditional on having an innovation increases. With a higher expected rent from experimenting with n , the agent's incentive to choose o in period 1 decreases, thus allowing the principal to provide him with a higher effort incentive.

5.2 Optimal contract for exploitation

This subsection considers the optimal contract for exploitation under FW. On the equilibrium path in period 2, the agent does not know the value of θ^n ; therefore, by the same argument as in (2), the agent always chooses to use o in period 2. Anticipating this, the principal optimally sets the period-2 contract to be $\beta^* = Y$ and $\alpha^* = -s(Y, \theta^o)$, which gives the agent a zero period-2 payoff. Under this period-2 contract, if the agent had deviated to using n in period 1 and hence privately knows θ^n , his period-2 payoff with an innovation outcome $\theta = \max\{\theta^o, \theta^n\}$ is $\alpha^* + \max_{\varepsilon} \{\varepsilon\beta^* - \psi(\varepsilon/\theta)\} = s(Y, \theta) - s(Y, \theta^o)$. Therefore, the agent's ex-ante expected period-2 payoff from using n in period 1 (i.e., his off-equilibrium path payoff) is $\int_{\theta^o}^{\bar{\theta}} s(Y, \theta) dF(\theta) - s(Y, \theta^o) > 0$.

Consider period 1 next. As before, the agent faces the same trade-off between an information rent from using n and a higher probability of getting the period-1 bonus from using o . Therefore, to motivate the agent to choose o in period 1, the period-1 contract (a, b) must satisfy the following conditions:

$$a + \bar{W}^o(b) \geq 0 \tag{16}$$

$$\bar{W}^o(b) \geq \bar{W}^n(b) + \int_{\theta^o}^{\bar{\theta}} s(Y, \theta) dF(\theta) - s(Y, \theta^o) \tag{17}$$

Proposition 4. *There exists a unique bonus threshold $\underline{b} > 0$ such that constraint (17) is satisfied if and only if $b \geq \underline{b}$. Under FW, the optimal period-1 contract that motivates exploitation is unique: $b^0 = \max\{Y, \underline{b}\}$, and $a^0 = -\bar{W}^o(b^0)$.*

When motivating exploitation under FW, the principal's payoff in period 2 is $S(\theta^o)$,¹⁵ while her payoff in period 1 is weakly lower than $S(\theta^o)$ because of the constraint that the period-1 bonus must be higher than $\underline{b}$. On the other hand, the principal's optimal contract for exploitation under TM gives her a total payoff of $S^{exploit} = 2S(\theta^o)$. Therefore:

Corollary 1. *The principal's highest expected payoff from inducing exploitation under FW is weakly lower than her highest expected payoff from inducing exploitation under TM.*

5.3 Uniqueness of equilibrium after each optimal contract

From the analysis in the previous two subsections, the optimal period-1 contract that induces the agent to engage in exploration with a probability of λ in period 1 is uniquely (a^λ, b^λ) , where (a^λ, b^λ) is characterized in Proposition 3 for $\lambda \in (0, 1]$ and in Proposition 4 for $\lambda = 0$. The following proposition states that the set of actions induced by each contract (a^λ, b^λ) is also unique.

Proposition 5. *For all $\lambda \in [0, 1]$, upon the agent accepting the period-1 contract (a^λ, b^λ) , the continuation game admits a unique equilibrium which involves the agent engaging in exploration with a probability of λ .*

Given the analysis thus far, the non-obvious parts of Proposition 5 are showing that (i) for any $\lambda \in (0, 1]$, the continuation game after contract (a^λ, b^λ) does not admit an equilibrium in which the agent chooses $\lambda = 0$, and (ii) the continuation game after contract (a^0, b^0) does not admit an equilibrium in which the agent chooses some $\lambda > 0$. The key step to showing the two properties is to verify that $\lim_{\lambda \rightarrow 0} \bar{b}(\lambda) = \underline{b}$; in turn, as $\bar{b}(\lambda)$ decreases with λ (from Lemma 6), this implies that $\bar{b}(\lambda) < \underline{b}$ for any $\lambda \in (0, 1]$.

To sustain an equilibrium in which the agent chooses $\lambda = 0$, the bonus must be at least $\underline{b}$ to satisfy condition (17). However, $\bar{b}(\lambda) < \underline{b}$ implies that $b^\lambda < \underline{b}$ for all $\lambda \in (0, 1]$, which thus

¹⁵As introduced in Section 3.3, $S(\theta)$ is the first best current period social surplus with cost efficiency θ .

establishes point (i). Next, to sustain an equilibrium in which the agent chooses $\lambda > 0$, the bonus must be exactly $\bar{b}(\lambda)$ or less than $\bar{b}(1)$ to satisfy conditions (14) or (15) respectively. However, $\underline{b} > \bar{b}(\lambda)$ implies that $b^0 > \bar{b}(\lambda)$ for all $\lambda \in (0, 1]$, which thus establishes point (ii).

5.4 Incentives for innovation

From Propositions 3 and 4, we observe that the period-1 incentive must be weakened to motivate more innovation attempt. The requirement for weak incentives is arguably most prominently noted in the multi-tasking literature (Holmström and Milgrom, 1991), in which the principal lowers the incentive for one task to prevent negligence on other uncontractible tasks. The parallel can be drawn here by viewing the two periods as different “tasks,” and a low incentive in period 1 induces the agent to focus on the period-2 rent, which then encourages him to experiment on n in period 1.

In terms of the incentive being weak only in period 1, the career concern model (Holmström, 1999) also has this feature, where a low incentive is sufficient to induce effort from a worker in his early career due to his reputational concern regarding his ability. By contrast, a low early incentive is in place here to encourage a worker to take on a risky experimentation.¹⁶ The low incentive in period 1 here also implies a low surplus from the principal-agent relationship in that period. The observation that economic partnerships often “start small” is well explained in the literature as a reputational building process to allow asymmetric information among partners to be gradually resolved.¹⁷ The model here does not study the gradual expansion within partnerships, but it provides a different rationale for low early stakes when innovations are involved: to generate an innovation incentive under incomplete contracts, low early stakes are needed to induce an agent to accumulate asymmetric information rather than to resolve it.

¹⁶Manso (2011) also points out that long-term contracts that encourage exploration must have low early incentives to tolerate early failures.

¹⁷See, for eg., Ghosh and Ray (1996); Watson (1999, 2002) and Halac (2012).

6 Comparative Statics for Exploration Payoffs

This section considers comparative statics and the choice of the monitoring environment. In Subsection 6.1, I first consider how the principal's exploration payoffs under FW are affected by the distribution of θ^n , focusing on the role of the agency issues in the model. Then, in Subsection 6.2, I use these results to speak to the principal's choice between TM and FW.

6.1 Comparative statics

Let the distribution of θ^n be parametrized by $k \in \mathcal{K}$, where $\mathcal{K}$ is an interval in $\mathbb{R}$. For each k , $F(\cdot; k)$ denotes a distribution on $[\underline{\theta}, \bar{\theta}(k)]$, with $0 < \underline{\theta} < \bar{\theta}(k) \leq 1$, and each $F(\cdot; k)$ has a density function $f(\cdot; k)$ that satisfies Assumption 2. Moreover, $f(\theta^n; k)$ is absolutely continuous in k for all $\theta^n \in [\underline{\theta}, \bar{\theta}(k)]$, and $\bar{\theta}(k)$ is also absolutely continuous.

Assumption 4. *If $k' > k$, then $\bar{\theta}(k') > \bar{\theta}(k)$ and $\frac{1-F(\theta^n; k')}{f(\theta^n; k')} > \frac{1-F(\theta^n; k)}{f(\theta^n; k)} \forall \theta^n \in [\underline{\theta}, \bar{\theta}(k)]$.*

By Assumption 4, k orders the distributions in terms of its upper bound and inverse hazard rate. An example of such a parametrization is the *family of uniform distributions* over $[\underline{\theta}, k]$ (i.e., for each k , $f(\theta^n; k) = 1/(k - \underline{\theta})$). Note that inverse hazard rate dominance implies first order stochastic dominance (i.e., $F(\theta^n; k)$ decreases with k).¹⁸ Therefore, a higher k means that the distribution is more concentrated at higher values of θ^n . Thus, a distribution with a higher k is henceforth also referred to as a *better* distribution.

In the trade-off between exploration and exploitation without agency frictions, a better distribution increases the exploration payoffs in *both* periods and thus favors exploration—referring to (1), a first-order stochastically dominating distribution increases the value at the left-hand side (i.e., the period-2 option value from innovation) and decreases the value at the right-hand side (i.e., the period-1 cost of innovation). However, as discussed below, the

¹⁸See Lemma 16 in Appendix B.

effects are less obvious in the presence of agency issues because a change in the distribution of θ^n also affects the distortions in the agent's effort incentives.

6.1.1 Distortion and payoff in period 2

Let $\{\alpha^\lambda(\theta; k), \beta^\lambda(\theta; k)\}_{\theta \in [\theta^o, \bar{\theta}(k)]}$ be the period-2 menu of contracts characterized in Proposition 2 for $\lambda \in (0, 1]$ under distribution $F(\cdot; k)$.

Lemma 7. *For all $\lambda \in (0, 1]$, if $k' > k$, then $\beta^\lambda(\theta; k') < \beta^\lambda(\theta; k) \forall \theta \in [\theta^o, \bar{\theta}(k)]$.*

A higher k leads to a point-wise decrease in the bonus schedule; hence, a better distribution of θ^n leads to a *worse* utilization of each innovation. This negative effect on the surplus arises only in the presence of agency issues and is otherwise absent in the standard exploration-exploitation trade-off of a single decision-maker. It arises because asymmetric information in period 2 creates information rents for the high types; therefore, when the distribution becomes concentrated at the high types, the cost of rent provision increases for the principal, so the principal distorts the incentives downward to decrease the rent provision.

Lemma 8. *For all $\lambda \in (0, 1]$, $\int_{\theta^o}^{\bar{\theta}} v(\beta^\lambda(\cdot; k), \theta) dF^\lambda(\theta; k)$ is strictly increasing in k – i.e., the principal's period-2 payoff from exploration with probability λ is strictly increasing in k .¹⁹*

Although a better distribution leads to more distortion of the effort incentive for each innovation, its effect is of only a second-order magnitude at the optimum. The gain from the higher probability of getting better innovations, which give higher surplus, dominates. Therefore, a better distribution still increases the principal's period-2 payoff. However, relative to a single decision-maker's problem, the requirement for asymmetric information to motivate innovation decreases the marginal gain from a better distribution of θ^n .

¹⁹Following (3), $F^\lambda(\theta; k) = 1 - \lambda + \lambda \left(F(\theta^o; k) + \int_{\theta^o}^{\theta} f(t; k) dt \right)$.

6.1.2 Effects on the information rent and the total payoff

To illustrate how the principal's total payoff changes with k , I need a few more notations. For each $F(\cdot; k)$, let $b^\lambda(k)$, $R^\lambda(k)$, and $\Pi^\lambda(k)$ be, respectively, the period-1 bonus characterized in Proposition 3, the agent's period-2 rent characterized in (12), and the principal's total payoff under the optimal contract that motivates exploration with probability λ .²⁰

Lemma 9. *Let $k < k'$. For any $\lambda \in (0, 1]$, if $R^\lambda(k) \leq R^\lambda(k')$ and $b^\lambda(k') \leq Y$, then $\Pi^\lambda(k) < \Pi^\lambda(k')$.*

In a single decision-maker's problem, a better distribution of θ^n decreases the cost of experimenting with n in period 1; this effect remains in the principal-agent relationship here. However, the agent's incentive to experiment with n in period 1 comes from the information rent in period 2, which, in turn, affects the effort incentive that the principal can give to the agent in period 1. In the model, the principal gets all the surplus in the relationship; thus, a higher information rent to the agent does not decrease the principal's total payoff because she can extract the expected rent from the agent using the period-1 fixed transfer. Instead, as Lemma 9 states, a higher rent can be good for the principal since it lets her give a stronger effort incentive in period 1, which increases the period-1 surplus if the incentive was being distorted downwards initially.

However, the agent's rent is endogenously determined. On the one hand, a better distribution of θ^n implies that the agent has a better chance of drawing a better innovation, which accrues a higher information rent; on the other hand, due to the decrease in bonuses as k

²⁰The principal gets all the surplus from the relationship, therefore:

$$\begin{aligned} \Pi^\lambda(k) &= \lambda \bar{s}^n(b^\lambda(k); k) + (1 - \lambda) \bar{s}^o(b^\lambda(k)) + \int_{\theta^o}^{\bar{\theta}(k)} s(\beta^\lambda(\theta; k), \theta) dF^\lambda(\theta; k); \\ \bar{s}^o(b) &= e^o(b)Y - \psi\left(\frac{e^o(b)}{\theta^o}\right), \text{ where } e^o(b) = \arg \max_e eb - \psi\left(\frac{e}{\theta^o}\right); \text{ and } \bar{s}^n(b; k) = e^n(b; k)Y - \\ &\int_{\underline{\theta}}^{\bar{\theta}(k)} \psi\left(\frac{e^n(b; k)}{\theta^n}\right) dF(\theta^n; k), \text{ where } e^n(b; k) = \arg \max_e eb - \int_{\underline{\theta}}^{\bar{\theta}(k)} \psi\left(\frac{e}{\theta^n}\right) dF(\theta^n; k). \end{aligned}$$

increases (i.e., Lemma 7), a better distribution also decreases the rent from each innovation. Therefore, it is not clear in general how the agent's period-2 information rent changes with k ; in turn, it is not clear how the period-1 surplus changes with k . The following provides an example in which a better distribution always increases the agent's period-2 rent.

Example 1. Suppose that $\{F(\cdot; k)\}_{\underline{\theta} < k \leq 1}$ is the family of uniform distributions over $[\underline{\theta}, k]$ and $\psi(x) = \xi x^2 \forall x \in [0, 1)$, where $\xi > 0$ is sufficiently big,²¹ and $\psi(x) = \infty \forall x \geq 1$. Under this parametrization, $R^\lambda(k)$ is strictly increasing in k for any $\lambda \in (0, 1]$. The proof is in Appendix B.

6.2 TM versus FW

From Corollary 1, if FW is preferred to TM, the principal must be inducing some exploration. Due to a lack of a closed-form solution, it is not feasible to rank the principal's total payoffs across the different exploration probabilities λ . Nevertheless, the above results describe how the exploration payoffs are affected by the distribution of θ^n , which has no effect on the principal's payoff under TM. Therefore, it provides a parametrization for a better distribution of θ^n in which the principal is more likely to favor FW over TM. The following complements the comparison by providing a sufficient condition for when there exists a level of exploration under which the principal's payoff is strictly higher than her payoff under TM.

Proposition 6. *If $b^\lambda = Y$ for some $\lambda > 0$,²² then the principal's total payoff under the optimal contract that induces exploration with probability λ is strictly greater than $S^{exploit}$; therefore, the principal must strictly prefer FW to TM.*

Proposition 6 implies that if the agency problem does not cause an effort distortion in period 1 to induce exploration with probability λ (recall that the first best effort incentive

²¹This cost function violates the Inada condition that $\lim_{x \uparrow 1} \psi(x) = \infty$, but if ξ is sufficiently big, the agent's effort choice is still always interior, which, in turn, ensures that all the results in Section 5 hold.

²²Note that this also holds when $\bar{b}(\lambda) > Y \forall \lambda$, as $\bar{b}(1) > Y$ implies that $b^1 = Y$.

is always a bonus of Y), then inducing exploration at that level will always be better than exploitation.²³

7 Conclusion

This paper illustrates how the monitoring environment affects a worker's incentive to innovate, and it characterizes the incentive scheme required to complement the monitoring environment. When formal property rights of innovations cannot be assigned to the worker, he has no incentive to innovate. By recognizing that private knowledge of an innovation is a substitute for its property rights, the firm can motivate innovation by allowing its worker to accrue private information about his innovation, which then compels the firm to share the innovation surplus with the worker via an information rent. This helps explain how workplaces are sometimes organized (seemingly inefficiently) to indirectly distribute rents to the workers. The intuitions here also apply to other relationships requiring an agent to make an uncontractible experimentation. For example, in a procurement relationship, the seller's incentive to make buyer-specific innovation attempts diminish when the innovation gains are expected to be observed and appropriated by the buyer. This might explain why some buyers would choose suppliers that are located far away (analogous to FW) despite the transportation costs incurred.

²³Numerical simulations of the parameterization in Example 1 reveal that for not so big values of $\underline{\theta}$, when fixing θ^o to be $(1 + \underline{\theta})/2$ (which ensures that $\theta^o \geq E[\theta^n]$ for all $k \leq 1$), b^1 will be Y for k sufficiently close to 1.

A Appendix: Proofs for Section 5

Proof of Lemma 2.

Proof. ε is differentiable using the implicit function theorem on (4). Differentiability of u then follows. Omitting the arguments, the partial derivatives of ε and u are as follows: $\varepsilon_\beta = \frac{\theta^2}{\psi''} > 0$, $\varepsilon_\theta = \frac{\psi'}{\psi''} + \frac{\varepsilon}{\theta} > 0$, $\varepsilon_{\beta\beta} = -\frac{\theta^3\psi'''}{(\psi'')^3} < 0$, $\varepsilon_{\theta\theta} = \frac{\psi'[2(\psi'')^2 - \psi' \cdot \psi''']}{\theta(\psi'')^3} > 0$, $\varepsilon_{\beta\theta} = \frac{\theta[2(\psi'')^2 - \psi' \cdot \psi''']}{(\psi'')^3} > 0$, $u_\beta = \varepsilon > 0$, $u_\theta = \psi' \cdot \frac{\varepsilon}{\theta^2} > 0$, $u_{\beta\beta} = \varepsilon_\beta > 0$, $u_{\theta\theta} = \frac{(\psi')^2}{\theta^2(\psi'')^2} > 0$, $u_{\beta\theta} = \varepsilon_\theta > 0$. $\square$

Proof of Lemma 3.

It follows from standard arguments—see, for e.g., [Salanié \(2005\)](#), chapter 2.3.1.

Proof of Proposition 2.

I first characterize the solution to program ($\mathcal{P}$). The characterization proceeds via two steps.

In Step 1, I consider the auxiliary program ($\tilde{\mathcal{P}}'$):

$$\Phi(\ddot{\beta}) := \max_{\beta(\cdot) \in \mathcal{B}; \beta(\theta^o) \geq \ddot{\beta} \geq 0} \lambda \int_{\theta^o}^{\bar{\theta}} \phi(\beta(\theta), \theta) f(\theta) d\theta. \quad (\tilde{\mathcal{P}}')$$

$\Phi(\ddot{\beta})$ is the principal's maximum expected payoff from the successful innovators when she must give at least $\ddot{\beta}$ to type θ^o . In Step 2, the optimal $\beta^\lambda(\theta^o)$ is pinned down by solving

$$\max_{\ddot{\beta}} \Phi(\ddot{\beta}) + s(\ddot{\beta}, \theta^o) F^\lambda(\theta^o). \quad (18)$$

By showing that the solution to ($\tilde{\mathcal{P}}'$) is unique for each $\ddot{\beta}$, the solution for (18) and its corresponding solution for ($\tilde{\mathcal{P}}'$) jointly form the solution to program ($\mathcal{P}$).

(Step 1) Solving the problem $\tilde{\mathcal{P}}'$.

Lemma 11 below gives the solution to $(\tilde{\mathcal{P}}')$. Lemma 10 gives the properties to prove Lemma 11 and Step 2 later.

Lemma 10. $\phi(\beta, \theta)$ is continuously differentiable in both of its arguments. For any $\theta \in [\theta^o, \bar{\theta}]$, $\arg \max_{\beta \geq 0} \phi(\beta, \theta)$ has a unique solution, which is denoted by $\hat{\beta}(\theta)$. For any $\theta \in [\theta^o, \bar{\theta}]$, (i) $\phi(\beta, \theta)$ is strictly concave in β for $\beta \in [0, Y]$; (ii) $\hat{\beta}(\theta)$ is characterized by $\phi_{\beta}(\hat{\beta}(\theta), \theta) = 0$; (iii) $\hat{\beta}(\bar{\theta}) = Y$; (iv) $\hat{\beta}(\theta)$ is differentiable, and $\frac{d}{d\theta}\hat{\beta}(\theta)$ is continuous; (v) $\hat{\beta}(\theta)$ is strictly increasing; and (vi) $\phi(\hat{\beta}(\theta), \theta)$ is continuous.

Proof. Differentiability of $\phi(\cdot)$ follows from differentiability of $\varepsilon(\cdot)$ and $\psi(\cdot)$.

$$\begin{aligned}\phi_{\beta}(\beta, \theta) &= \varepsilon_{\beta}(\beta, \theta)Y - \frac{1}{\theta}\psi'\left(\frac{\varepsilon(\beta, \theta)}{\theta}\right) - u_{\beta\theta}(\beta, \theta)H(\theta) \\ &= \varepsilon_{\beta}(\beta, \theta)[Y - \beta] - \varepsilon_{\theta}(\beta, \theta)H(\theta),\end{aligned}\tag{19}$$

$$\phi_{\beta\beta}(\beta, \theta) = \varepsilon_{\beta\beta}(\beta, \theta)[Y - \beta] - \varepsilon_{\beta}(\beta, \theta) - \varepsilon_{\beta\theta}(\beta, \theta)H(\theta),\tag{20}$$

which is strictly negative when $\beta \leq Y$. This establishes point (i). From (19), $\phi_{\beta}(\beta, \theta) < 0$ for $\beta > Y$; therefore, the optimal β must be less than Y .²⁴ Together with point (i), $\hat{\beta}(\theta)$ is unique and it is characterized by the FOC, which thus establishes point (ii). Point (iii) then follows from $H(\bar{\theta}) = 0$. Next,

$$\phi_{\theta\beta}(\beta, \theta) = \varepsilon_{\theta\beta}(\beta, \theta)[Y - \beta] - \varepsilon_{\theta\theta}(\beta, \theta)H(\theta) - \varepsilon_{\theta}(\beta, \theta)H_{\theta}(\theta).\tag{21}$$

Using point (ii) and FOC (19), $Y - \hat{\beta}(\theta) = \frac{\varepsilon_{\theta}(\hat{\beta}(\theta), \theta)H(\theta)}{\varepsilon_{\beta}(\hat{\beta}(\theta), \theta)}$. Substitute this into (21) and with

²⁴From here, it is readily noted that the principal's objective is strictly quasi-concave in β . Therefore, offering stochastic contracts is never optimal for the principal, which addresses the remark in fn. 11.

some algebra (and dropping the arguments without confusion),

$$\begin{aligned}\phi_{\theta\beta}(\beta, \theta) \Big|_{\beta=\hat{\beta}(\theta)} &= \varepsilon_{\beta\theta} \frac{\varepsilon_{\theta} H(\theta)}{\varepsilon_{\beta}} - \varepsilon_{\theta\theta} H(\theta) - \varepsilon_{\theta} H_{\theta}(\theta) \\ &= \frac{[2(\psi'')^2 - \psi' \psi''']}{\theta^2 (\psi'')^2} \varepsilon H(\theta) - \varepsilon_{\theta} H_{\theta}(\theta) > 0,\end{aligned}\tag{22}$$

where the inequality follows from Assumptions 1 and 2. By the implicit function theorem, $\frac{d}{d\theta} \hat{\beta}(\theta) = -\frac{\phi_{\theta\beta}(\hat{\beta}(\theta), \theta)}{\phi_{\beta\beta}(\hat{\beta}(\theta), \theta)} > 0$, and it is also continuous. This establishes points (iv) and (v). Since ϕ is continuous in $\theta \in [\theta^o, \bar{\theta}]$, by the Maximum theorem, $\phi(\hat{\beta}(\theta), \theta)$ is continuous, which establishes point (vi). $\square$

Lemma 11. Fix $\ddot{\beta} > 0$ and let $\tilde{\beta}^*(\cdot)$ be the solution to program $(\tilde{\mathcal{P}}')$. $\tilde{\beta}^*(\cdot)$ is uniquely characterized by the following:

1. If $\ddot{\beta} \geq Y$, then $\tilde{\beta}^*(\theta) = \ddot{\beta} \forall \theta \in [\theta^o, \bar{\theta}]$.
2. If $\ddot{\beta} \leq \hat{\beta}(\theta^o)$, then $\tilde{\beta}^*(\theta) = \hat{\beta}(\theta) \forall \theta \in [\theta^o, \bar{\theta}]$.
3. If $\ddot{\beta} \in (\hat{\beta}(\theta^o), Y)$, then

$$\tilde{\beta}^*(\theta) = \begin{cases} \hat{\beta}(\theta) & , \forall \theta \geq \hat{\beta}^{-1}(\ddot{\beta}) \\ \ddot{\beta} & , \forall \theta < \hat{\beta}^{-1}(\ddot{\beta}) \end{cases}.\tag{23}$$

Proof. Case 1 is trivially true because $\phi_{\beta}(\beta, \theta) < 0 \forall \theta$ for $\beta > Y$. Case 2 follows from $\hat{\beta}(\cdot)$ being point-wise optimal for all θ . For Case 3, first note that $\hat{\beta}^{-1}(\cdot)$ is well-defined because $\hat{\beta}(\cdot)$ is strictly increasing. Ignore the monotonicity constraint for the moment and just consider the constraint that $\beta(\theta) \geq \ddot{\beta} \forall \theta$. For any $\theta \geq \hat{\beta}^{-1}(\ddot{\beta})$, $\tilde{\beta}^*$ maximizes ϕ because $\hat{\beta}$ is the point-wise optimum. Next, consider any $\theta < \hat{\beta}^{-1}(\ddot{\beta})$. Since ϕ is strictly concave in β for $\beta \leq Y$ and $\phi_{\beta}(\hat{\beta}(\theta), \theta) = 0$, this implies that for any $\beta', \beta'' \leq Y$ such that

$\hat{\beta}(\theta) \leq \beta' < \beta''$, $\phi(\beta', \theta) > \phi(\beta'', \theta)$. Since the bonus must be at least $\ddot{\beta}$, $\ddot{\beta}$ is the constrained optimum for any $\theta < \hat{\beta}^{-1}(\ddot{\beta})$. Therefore, $\ddot{\beta}^*$ maximizes ϕ for all θ under the constraint that $\beta(\theta) \geq \ddot{\beta} \forall \theta$. Since it is also monotonic, it is the solution to program $(\tilde{\mathcal{P}}')$. $\square$

(Step 2) Solve for $\ddot{\beta}$.

Lemma 12. $\Phi(\ddot{\beta})$ is strictly concave when $\ddot{\beta} < Y$.

Proof. $\Phi(\ddot{\beta})$ can be written as

$$\Phi(\ddot{\beta}) = \lambda \left(\int_{\theta^o}^{\hat{\beta}^{-1}(\ddot{\beta})} \phi(\ddot{\beta}, \theta) f(\theta) d\theta + \int_{\hat{\beta}^{-1}(\ddot{\beta})}^{\bar{\theta}} \phi(\hat{\beta}(\theta), \theta) f(\theta) d\theta \right).$$

Since $\hat{\beta}(\cdot)$ is strictly increasing and differentiable, $\hat{\beta}^{-1}(\cdot)$ is also strictly increasing and differentiable with derivative $\frac{1}{\hat{\beta}'(\hat{\beta}^{-1}(\ddot{\beta}))}$, which is continuous because $\hat{\beta}'(\cdot)$ is continuous. Therefore, Φ is differentiable by Leibniz's rule, and

$$\begin{aligned} \frac{d}{d\ddot{\beta}} \Phi(\ddot{\beta}) &= \lambda \left(\underbrace{\phi(\ddot{\beta}, \hat{\beta}^{-1}(\ddot{\beta})) - \phi(\ddot{\beta}, \hat{\beta}^{-1}(\ddot{\beta}))}_{=0} \right) f(\hat{\beta}^{-1}(\ddot{\beta})) \left(\frac{1}{\hat{\beta}'(\hat{\beta}^{-1}(\ddot{\beta}))} \right) \\ &+ \lambda \int_{\theta^o}^{\hat{\beta}^{-1}(\ddot{\beta})} \underbrace{\phi_{\beta}(\ddot{\beta}, \theta)}_{<0} f(\theta) d\theta < 0. \end{aligned}$$

$\phi_{\beta}(\ddot{\beta}, \theta) < 0 \forall \theta \in [\theta^o, \hat{\beta}^{-1}(\ddot{\beta})]$ because $\phi_{\beta\beta} < 0$ and $\ddot{\beta} > \hat{\beta}(\theta)$. Differentiating again,

$$\begin{aligned} \frac{d^2}{d\ddot{\beta}^2} \Phi(\ddot{\beta}) &= \lambda \underbrace{\phi_{\beta}(\ddot{\beta}, \hat{\beta}^{-1}(\ddot{\beta}))}_{=0} f(\hat{\beta}^{-1}(\ddot{\beta})) \left(\frac{1}{\hat{\beta}'(\hat{\beta}^{-1}(\ddot{\beta}))} \right) \\ &+ \lambda \int_{\theta^o}^{\hat{\beta}^{-1}(\ddot{\beta})} \underbrace{\phi_{\beta\beta}(\ddot{\beta}, \theta)}_{<0} f(\theta) d\theta < 0 \end{aligned}$$

$\square$

Lemma 13. $s(\ddot{\beta}, \theta^o) F^\lambda(\theta^o)$ is strictly concave in $\ddot{\beta}$ when $\ddot{\beta} < Y$.

Proof.

$$\frac{d}{d\ddot{\beta}} s(\ddot{\beta}, \theta^o) = \varepsilon_\beta(\ddot{\beta}, \theta^o) Y - \frac{\varepsilon_\beta(\ddot{\beta}, \theta^o)}{\theta^o} \psi' \left(\frac{\varepsilon(\ddot{\beta}, \theta^o)}{\theta^o} \right) = \varepsilon_\beta(\ddot{\beta}, \theta^o) [Y - \ddot{\beta}], \quad (24)$$

which is positive whenever $\ddot{\beta} < Y$. Differentiating again, $\frac{d^2}{d\ddot{\beta}^2} s(\ddot{\beta}, \theta^o) = \varepsilon_{\beta\beta}(\ddot{\beta}, \theta^o) [Y - \ddot{\beta}] - \varepsilon_\beta(\ddot{\beta}, \theta^o) < 0$. $\square$

Lemmas 12 and 13 jointly imply that $\Phi(\ddot{\beta}) + s(\ddot{\beta}, \theta) F^\lambda(\theta^o)$ is strictly concave when $\ddot{\beta} \in [\hat{\beta}(\theta^o), Y]$. Moreover, the optimum must be in the interior of $[\hat{\beta}(\theta^o), Y]$. To see why, notice that $\left. \frac{d}{d\ddot{\beta}} \Phi(\ddot{\beta}) \right|_{\ddot{\beta}=\hat{\beta}(\theta^o)} = 0$, while $\left. \frac{d}{d\ddot{\beta}} s(\ddot{\beta}, \theta^o) \right|_{\ddot{\beta}=\hat{\beta}(\theta^o)} > 0$; therefore, $\ddot{\beta} > \hat{\beta}(\theta^o)$. Similarly, $\left. \frac{d}{d\ddot{\beta}} \Phi(\ddot{\beta}) \right|_{\ddot{\beta}=Y} < 0$, while $\left. \frac{d}{d\ddot{\beta}} s(\ddot{\beta}, \theta^o) \right|_{\ddot{\beta}=Y} = 0$; therefore, $\ddot{\beta} < Y$. This implies that the solution to (18) is characterized by its first-order condition, which is condition (10) in Proposition 2 with $T^\lambda = \hat{\beta}^{-1}(\ddot{\beta})$. The strict concavity also implies that the solution is unique; therefore, the solution to $(\tilde{\mathcal{P}}')$ is unique. It is readily verified that objective (18) is strictly submodular in $\ddot{\beta}$ and λ ; therefore, the solution is decreasing in λ . Since $\hat{\beta}^{-1}$ is strictly increasing, T^λ is also decreasing in λ . Next, notice that $\tilde{\beta}^*(\cdot)$ is continuous everywhere, differentiable everywhere except (possibly) at T^λ , and strictly increasing for $\theta \geq T^\lambda$. Since these properties hold for any $\ddot{\beta}$, they carry over to $\beta^\lambda(\cdot)$. Finally, $\alpha^\lambda(\cdot)$ is obtained from Lemma 3 with $\frac{d}{d\theta} \alpha^\lambda(\theta) = -u_\beta(\beta^\lambda(\theta), \theta) \left(\frac{d}{d\theta} \beta^\lambda(\theta) \right) \leq 0$ whenever the derivative exists.

Showing that the value of program $(\mathcal{P})$ increases with λ .

Note that the characterization proof above holds if the non-increasing inverse hazard rate property in Assumption 2 only holds for $\theta \in (\theta^o, \bar{\theta}]$. Let CDF $\hat{F}(\theta; \lambda) = F^\lambda(\theta) \forall \theta \in [\theta^o, \bar{\theta}]$, and let the corresponding pdf be $\hat{f}(\cdot; \lambda)$. It is readily noted $\frac{1-\hat{F}(\theta; \lambda)}{\hat{f}(\theta; \lambda)} = H(\theta; \lambda) \forall \theta \in [\theta^o, \bar{\theta}]$,

and $\frac{1-\hat{F}(\theta;\lambda)}{\hat{f}(\theta;\lambda)}$ is increasing in λ . This implies that $\hat{F}(\cdot; \lambda)$ is parametrized by λ as in k in Assumption 4, except that $\bar{\theta}(\lambda) = \bar{\theta}(\lambda') \forall \lambda$. However, by Remark 2 in the proof of Lemma 8, the arguments for Lemma 8 continue to hold. Therefore, the value of program ($\mathcal{P}$) increases with λ .

Proof of Lemma 4.

Proof. The property that $Innov^\lambda(\cdot)$ is continuous is immediate. It is readily verified that $s_\beta(\beta, \theta) > 0 \forall \beta < Y$. Since $\beta^\lambda(\cdot)$ is increasing and $\beta^\lambda(\theta) < Y \forall \theta \leq \bar{\theta}$, $Innov^\lambda(\cdot)$ is strictly increasing, and $s(\beta^\lambda(\theta^o), \theta^o) < s(Y, \theta^o)$ (i.e., $Innov^\lambda(\theta^o) < 0$). Next, program ($\mathcal{P}$) has a feasible solution that achieves $s(Y, \theta^o)$: set $\beta(\theta) = Y$ and $\alpha(\theta) = -s(Y, \theta^o) \forall \theta$. This implies that $\int_{\theta^o}^{\bar{\theta}} (s(\beta^\lambda(\theta), \theta) - \int_{\theta^o}^{\theta} u_\theta(\beta^\lambda(t), t) dt) dF^\lambda(\theta) \geq s(Y, \theta^o)$. Therefore, $E[Innov^\lambda(\theta)] \geq \int_{\theta^o}^{\bar{\theta}} (\int_{\theta^o}^{\theta} u_\theta(\beta^\lambda(t), t) dt) dF^\lambda(\theta) > 0$. Finally, for any $\lambda < \lambda'$, from Proposition 2, $\beta^\lambda(\theta) = \beta^{\lambda'}(\theta) = \hat{\beta}(\theta) \forall \theta \geq T^\lambda$, which implies that $Innov^\lambda(\theta) = Innov^{\lambda'}(\theta) \forall \theta \geq T^\lambda$, and $\forall \theta < T^\lambda$, $\beta^\lambda(\theta) = \hat{\beta}(T^\lambda) > \beta^{\lambda'}(\theta)$, which implies that $Innov^\lambda(\theta) > Innov^{\lambda'}(\theta)$. $\square$

Proof of Lemma 6.

Proof. Since W^τ is supermodular, $e^\tau(b)$ is strictly increasing. Concavity of $W^\tau(e, b)$ in e implies that $e^\tau(b)$ is characterized by the first-order condition. Therefore,

$$b = \frac{1}{\theta^o} \psi' \left(\frac{e^o(b)}{\theta^o} \right) \quad , \quad b = E \left[\frac{1}{\theta^n} \psi' \left(\frac{e^n(b)}{\theta^n} \right) \right]. \quad (25)$$

This implies that for any $b > 0$,

$$\frac{1}{\theta^o} \psi' \left(\frac{e^o(b)}{\theta^o} \right) = E \left[\frac{1}{\theta^n} \psi' \left(\frac{e^n(b)}{\theta^n} \right) \right] > \frac{1}{E[\theta^n]} \psi' \left(\frac{e^n(b)}{E[\theta^n]} \right) \geq \frac{1}{\theta^o} \psi' \left(\frac{e^n(b)}{\theta^o} \right).$$

Since $\psi'(\cdot)$ is strictly increasing, $e^o(b) > e^n(b)$.

Next, let $\Delta(b) := \bar{W}^o(b) - \bar{W}^n(b) - R^\lambda$. Since $\lim_{b \rightarrow 0} e^\tau(b) = 0 \ \forall \tau$, $\lim_{b \rightarrow 0} \Delta(b) = -R^\lambda < 0$. Therefore, there exists a sufficiently small b such that $\Delta(b) < 0$. By the envelope theorem, $\Delta'(b) = e^o(b) - e^n(b) > 0 \ \forall b > 0$, which implies that $\Delta(b)$ is strictly increasing. Notice that $e^o(b) = \varepsilon(b, \theta^o)$. $e^n(b) < e^o(b)$ implies that there exists $\hat{\theta} < \theta^o$ such that $e^n(b) = \varepsilon(b, \hat{\theta})$. Since ε is supermodular—see the proof for Lemma 2— $e^{o'}(b) > e^{n'}(b)$, so $\Delta''(b) > 0$. Therefore, $\Delta(b)$ crosses 0 exactly once, and $\bar{b}(\lambda) = \Delta^{-1}(0)$. $\square$

Proof of Proposition 3.

Proof. The contract for $\lambda \in (0, 1)$ is already pinned down by condition (14). For $\lambda = 1$, it suffices to show that the expected period-1 surplus generated by b is strictly concave. Since $\frac{d}{db} [e^n(b)Y - E[\psi(\frac{e^n(b)}{\theta^n})]] = \frac{de^n(b)}{db} (Y - b)$, which is positive if and only if $b \leq Y$, and the constraint on b is an upper bound, it must hold that $b^\lambda \leq Y$. Next, $\frac{d^2}{db^2} [e^n(b)Y - E[\psi(\frac{e^n(b)}{\theta^n})]] = -\frac{de^n(b)}{db} + \frac{d^2e^n(b)}{db^2} (Y - b)$; therefore, the surplus is strictly concave if $\frac{d^2e^n(b)}{db^2} \leq 0$. Twice differentiating the FOC for $e^n(b)$ in (25) with b , we get

$$-E\left[\left(\frac{1}{\theta^n}\right)^3 \psi''' \left(\frac{e^n(b)}{\theta^n}\right)\right] \left(\frac{d}{db}(e^n(b))\right)^2 - E\left[\left(\frac{1}{\theta^n}\right)^2 \psi'' \left(\frac{e^n(b)}{\theta^n}\right)\right] \frac{d^2}{db^2}(e^n(b)) = 0.$$

Since $\psi'''(\cdot) \geq 0$, it must hold that $\frac{d^2}{db^2}(e^n(b)) \leq 0$.

Finally, from the proof of Lemma 6 and the observation that $\Delta(b)$ is point-wise decreasing in the value of R^λ , $\bar{b}(\lambda)$ is increasing in R^λ . For any $\lambda < \lambda'$, as established in the proof of Lemma 4, $\beta^\lambda(\theta) = \beta^{\lambda'}(\theta) \ \forall \theta \in [T^\lambda, \bar{\theta}]$, and $\beta^\lambda(\theta) > \beta^{\lambda'}(\theta) \ \forall \theta \in [\theta^o, T^\lambda)$. From (12), this implies that $R^\lambda > R^{\lambda'}$, which implies that $\bar{b}(\lambda) > \bar{b}(\lambda')$. If $\lambda' < 1$, then $b^{\lambda'} = \bar{b}(\lambda') < \bar{b}(\lambda) = b^\lambda$; if $\lambda' = 1$, then $b^{\lambda'} \leq \bar{b}(\lambda') < \bar{b}(\lambda) = b^\lambda$. $\square$

Proof of Proposition 4.

Proof. The existence of the unique threshold $\underline{b}$ follows from the same argument for Lemma 6. The expected period-1 social surplus from a contract (a, b) is $e^o(b)Y - \psi\left(\frac{e^o(b)}{\theta^o}\right) = s(b, \theta^o)$. By an analogous argument to that for Proposition 3, $s(b, \theta^o)$ is strictly concave in b , which implies that $b^* = \max\{Y, \underline{b}\}$. Since the agent's on-equilibrium period-2 payoff is 0, $a^* = -\bar{W}^o(b^*)$. $\square$

Proof of Proposition 5.

We first prove the following result:

Lemma 14. $\bar{b}(\lambda) < \underline{b} \forall \lambda \in (0, 1]$.

Proof. Recall that T^λ is characterized in (10), which can be rewritten as

$$\frac{\lambda}{F^\lambda(\theta^o)} \int_{\theta^o}^{T^\lambda} \phi_\beta(\hat{\beta}(T^\lambda), \theta) f(\theta) d\theta + s_\beta(\hat{\beta}(T^\lambda), \theta^o) = 0.$$

Using (3), it is readily observed that $\frac{\lambda}{F^\lambda(\theta^o)}$ is strictly increasing in λ . Fix any small $\varepsilon > 0$ and let $\hat{t} = \bar{\theta} - \varepsilon$. From Lemma 13 and equation (24), for any $\beta < Y$, $s_\beta(\beta, \theta^o) > 0$ and is strictly decreasing in β , with $s_\beta(Y, \theta^o) = 0$. As $\hat{\beta}(\hat{t}) < Y$, $s_\beta(\hat{\beta}(\hat{t}), \theta^o) > 0$. Moreover, from the properties of ϕ in Lemma 10, $\int_{\theta^o}^{\hat{t}} \phi_\beta(\hat{\beta}(\hat{t}), \theta) f(\theta) d\theta < 0$, so there exists $\delta > 0$ such that $\frac{\delta}{F^\delta(\theta^o)} \int_{\theta^o}^{\hat{t}} \phi_\beta(\hat{\beta}(\hat{t}), \theta) f(\theta) d\theta + s_\beta(\hat{\beta}(\hat{t}), \theta^o) = 0$. Using the argument to establish that T^λ is strictly decreasing in λ (in Proposition 2), it implies that for all $\lambda < \delta$, $T^\lambda > \bar{\theta} - \varepsilon$ —i.e., $\lambda \in (0, \delta) \implies T^\lambda \in (\bar{\theta} - \varepsilon, \bar{\theta})$. Therefore, $\lim_{\lambda \downarrow 0} T^\lambda = \bar{\theta}$. Next, using (12) and the property of β^λ characterized in Proposition 2, R^λ can be expressed as

$$\begin{aligned} R^\lambda = & \int_{T^\lambda}^{\bar{\theta}} \left[\int_{T^\lambda}^{\theta} u_\theta(\hat{\beta}(t), t) dt + \int_{\theta^o}^{T^\lambda} u_\theta(\hat{\beta}(T^\lambda), t) dt \right] dF(\theta) \\ & + \int_{\theta^o}^{T^\lambda} \left[\int_{\theta^o}^{\theta} u_\theta(\hat{\beta}(T^\lambda), t) dt \right] dF(\theta). \end{aligned}$$

Therefore, $\lim_{\lambda \downarrow 0} R^\lambda = \lim_{T^\lambda \uparrow \bar{\theta}} R^\lambda = \int_{\theta^o}^{\bar{\theta}} \left[\int_{\theta^o}^{\theta} u_\theta(Y, t) dt \right] dF(\theta)$. From (26) below, $u_\theta(Y, \theta) = s_\theta(Y, \theta)$. Therefore,

$$\begin{aligned} \lim_{\lambda \downarrow 0} R^\lambda &= \int_{\theta^o}^{\bar{\theta}} \left[\int_{\theta^o}^{\theta} s_\theta(Y, t) dt \right] dF(\theta) \\ &= \int_{\theta^o}^{\bar{\theta}} s(Y, \theta) - s(Y, \theta^o) dF(\theta) = \int_{\theta^o}^{\bar{\theta}} s(Y, \theta) dF(\theta) - s(Y, \theta^o) \end{aligned}$$

This implies that

$$\lim_{\lambda \downarrow 0} (\bar{W}^o(b) - \bar{W}^n(b) - R^\lambda) = \bar{W}^o(b) - \bar{W}^n(b) - \left[\int_{\theta^o}^{\bar{\theta}} s(Y, \theta) dF(\theta) - s(Y, \theta^o) \right].$$

Comparing (14) and (17), it thus follows that $\lim_{\lambda \downarrow 0} \bar{b}(\lambda) = \underline{b}$. As $\bar{b}(\lambda)$ decreases with λ (see Lemma 6), $\bar{b}(\lambda) < \underline{b} \forall \lambda > 0$. $\square$

We are ready to prove Proposition 5 now.

Proof. Consider contract (a^1, b^1) first. Consider sustaining an equilibrium in the continuation game with $\lambda' \neq 1$. If $\lambda' \in (0, 1)$, the period-1 bonus must satisfy constraint (14); however, $\bar{W}^n(b) + R^{\lambda'} > \bar{W}^o(b)$ for all $b < \bar{b}(\lambda')$, whereas $b^1 \leq \bar{b}(1) < \bar{b}(\lambda')$. If $\lambda' = 0$, the period-1 bonus must satisfy constraint (17); however, the constraint is violated whenever $b < \underline{b}$, and $b^1 \leq \bar{b}(1) < \underline{b}$. Therefore, the continuation game after (a^1, b^1) cannot admit any equilibrium with $\lambda \in [0, 1)$.

Next, consider contract (a^λ, b^λ) for any $\lambda \in (0, 1)$. Consider sustaining an equilibrium in the continuation game with $\lambda' \neq \lambda$. As $\bar{b}(\cdot)$ is strictly monotonic, b^λ does not satisfy constraint (14) for any $\lambda' \in (0, 1) \setminus \{\lambda\}$. Moreover, as $b^\lambda > \bar{b}(1)$, $\bar{W}^n(b) + R^1 < \bar{W}^o(b)$, so b^λ also cannot admit an equilibrium with $\lambda' = 1$. Next, $b^\lambda < \underline{b}$, which implies that b^λ violates constraint (17), so b^λ also cannot admit an equilibrium with $\lambda' = 0$. Therefore, the continuation game after (a^λ, b^λ) cannot admit any equilibrium with $\lambda' \neq \lambda$.

Finally, contract consider (a^0, b^0) . Consider sustaining an equilibrium in the continuation game with $\lambda' \neq 0$. As $b^0 \geq \underline{b} > \bar{b}(\lambda')$, constraint (14) for $\lambda' \in (0, 1)$ is always violated by b^0 , so b^0 cannot sustain an equilibrium with $\lambda' \in (0, 1)$. Next, $b^0 > \bar{b}(1)$ also implies that $\bar{W}^n(b^0) + R^1 < \bar{W}^o(b^0)$ (i.e., violates (15)), so b^0 also cannot sustain an equilibrium with $\lambda' = 1$. Therefore, the continuation game after (a^0, b^0) cannot admit any equilibrium with $\lambda' \in (0, 1]$. $\square$

B Appendix: Proofs for Section 6

Notations: Throughout this section, let $H(\theta; k) = \frac{1-F(\theta; k)}{f(\theta; k)}$, let $\hat{\beta}(\cdot; k)$ be the bonus schedule characterized in (9) under distribution $F(\cdot; k)$, let $T^\lambda(k)$ be the highest bunching type characterized in (10) under distribution $F(\cdot; k)$, and let $\tilde{\beta}^\lambda(k) = \hat{\beta}(T^\lambda; k)$

The following properties will be used in the subsequent proofs.

Lemma 15. $s_\theta(\beta, \theta) = \varepsilon_\theta(\beta, \theta)[Y - \beta] + u_\theta(\beta, \theta)$ and $s_{\theta\beta}(\beta, \theta) = \varepsilon_{\theta\beta}(\beta, \theta)[Y - \beta]$. Therefore, $\forall \beta \leq Y$, $s_\theta(\beta, \theta) > 0$ and $s_{\theta\beta}(\beta, \theta) > 0$.

Proof.

$$\begin{aligned}
s_\theta(\beta, \theta) &= \varepsilon_\theta(\beta, \theta)Y - \psi' \left(\frac{\varepsilon(\beta, \theta)}{\theta} \right) \left[\frac{\theta \varepsilon_\theta(\beta, \theta) - \varepsilon(\beta, \theta)}{\theta^2} \right] \\
&= \varepsilon_\theta(\beta, \theta) \left[Y - \frac{1}{\theta} \psi' \left(\frac{\varepsilon(\beta, \theta)}{\theta} \right) \right] + \psi' \left(\frac{\varepsilon(\beta, \theta)}{\theta} \right) \frac{\varepsilon(\beta, \theta)}{\theta^2} \\
&= \varepsilon_\theta(\beta, \theta)[Y - \beta] + u_\theta(\beta, \theta)
\end{aligned} \tag{26}$$

By noting that $u_{\theta\beta}(\beta, \theta) = \varepsilon_{\theta\beta}(\beta, \theta)$, it is immediate that $s_{\theta\beta}(\beta, \theta) = \varepsilon_{\theta\beta}(\beta, \theta)[Y - \beta]$. $\square$

Lemma 16. Under Assumption 4, $k'' > k'$ implies that $F(\theta^n; k'') < F(\theta^n; k') \forall \theta^n \in [\underline{\theta}, \bar{\theta}(k')]$.

Proof. Notice that $\int_{\underline{\theta}}^{\theta} \frac{1}{H(t;k)} dt = -\log [1 - F(\theta; k)]$. For any $\theta \in [\underline{\theta}, \bar{\theta}(k')]$,

$$\begin{aligned} \int_{\underline{\theta}}^{\theta} \frac{1}{H(t;k')} dt &> \int_{\underline{\theta}}^{\theta} \frac{1}{H(t;k'')} dt \implies -\log [1 - F(\theta; k')] > -\log [1 - F(\theta; k'')] \\ &\implies F(\theta; k') > F(\theta; k'') \end{aligned}$$

□

Proof of Lemma 7.

Proof. Let $k < k'$. It is readily verified from (9) that $H(\theta; k') > H(\theta; k) \implies \hat{\beta}(\theta; k') < \hat{\beta}(\theta; k)$. Therefore, we only need to show that $\ddot{\beta}^\lambda(k') < \ddot{\beta}^\lambda(k)$. Let $\hat{\beta}^{-1}(\cdot; k)$ denote the inverse of $\hat{\beta}(\cdot; k)$. Using (19), condition (10) can be written as

$$\begin{aligned} \lambda \int_{\theta^o}^{\hat{\beta}^{-1}(\ddot{\beta}^\lambda(k); k)} \left(\varepsilon_\beta \left(\ddot{\beta}^\lambda(k), \theta \right) \left(Y - \ddot{\beta}^\lambda(k) \right) f(\theta; k) - \varepsilon_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) [1 - F(\theta; k)] \right) d\theta \\ + s_\beta \left(\ddot{\beta}^\lambda(k), \theta^o \right) F^\lambda(\theta^o; k) = 0 \end{aligned} \quad (27)$$

By the implicit function theorem, $\frac{d}{dk} \ddot{\beta}^\lambda(k) = -\frac{\frac{\partial(eq \ 27)}{\partial k}}{\frac{\partial(eq \ 27)}{\partial \beta}}$. From Lemmas 12 and 13, $\frac{\partial(eq \ 27)}{\partial \beta} < 0$. I show that $\frac{\partial(eq \ 27)}{\partial k} < 0$ next.

$$\begin{aligned} \frac{\partial(eq \ 27)}{\partial k} &= \underbrace{\lambda \phi_\beta \left(\ddot{\beta}^\lambda(k), T^\lambda(k) \right) f \left(T^\lambda(k); k \right) \left(\hat{\beta}_k^{-1} \left(\ddot{\beta}^\lambda(k); k \right) \right)}_{=0} + \underbrace{s_\beta \left(\ddot{\beta}^\lambda(k), \theta^o \right)}_{>0} \underbrace{F_k(\theta^o; k)}_{<0} \\ &\quad + \int_{\theta^o}^{\hat{\beta}^{-1}(\ddot{\beta}^\lambda(k); k)} \left[\underbrace{\varepsilon_\beta \left(\ddot{\beta}^\lambda(k), \theta \right)}_{>0} \underbrace{\left(Y - \ddot{\beta}^\lambda(k) \right) f_k(\theta; k)}_{>0} + \underbrace{\varepsilon_\theta \left(\ddot{\beta}^\lambda(k), \theta \right)}_{>0} \underbrace{F_k(\theta; k)}_{<0} \right] d\theta \end{aligned}$$

Therefore, if the second line is negative, $\frac{\partial(eq \ 27)}{\partial k} < 0$. Notice that this immediately holds if $f_k(\theta; k) \leq 0$. Suppose that $f_k(\theta; k) > 0$ instead. Since $\theta \leq T^\lambda(k)$ in this region, $\ddot{\beta}^\lambda(k) \geq$

$\hat{\beta}(\theta; k)$. Equations (19) and (20) jointly imply that

$$\varepsilon_{\beta}(\ddot{\beta}^{\lambda}(k), \theta) [Y - \ddot{\beta}^{\lambda}(k)] - \varepsilon_{\theta}(\ddot{\beta}^{\lambda}(k), \theta) H(\theta; k) \leq 0 \iff Y - \ddot{\beta}^{\lambda}(k) \leq \frac{\varepsilon_{\theta}(\ddot{\beta}^{\lambda}(k), \theta) H(\theta; k)}{\varepsilon_{\beta}(\ddot{\beta}^{\lambda}(k), \theta)}.$$

Substitute this into the above, we have

$$\begin{aligned} & \varepsilon_{\beta}(\ddot{\beta}^{\lambda}(k), \theta) (Y - \ddot{\beta}^{\lambda}(k)) f_k(\theta; k) + \varepsilon_{\theta}(\ddot{\beta}^{\lambda}(k), \theta) F_k(\theta; k) \\ \leq & \varepsilon_{\beta}(\ddot{\beta}^{\lambda}(k), \theta) \left(\frac{\varepsilon_{\theta}(\ddot{\beta}^{\lambda}(k), \theta) H(\theta; k)}{\varepsilon_{\beta}(\ddot{\beta}^{\lambda}(k), \theta)} \right) f_k(\theta; k) + \varepsilon_{\theta}(\ddot{\beta}^{\lambda}(k), \theta) F_k(\theta; k) \\ = & \varepsilon_{\theta}(\ddot{\beta}^{\lambda}(k), \theta) [H(\theta; k) f_k(\theta; k) + F_k(\theta; k)], \end{aligned}$$

which is negative because $H_k(\theta; k) > 0$ and $H_k(\theta; k) = -\frac{1}{f(\theta; k)} [H(\theta; k) f_k(\theta; k) + F_k(\theta; k)]$. $\square$

Proof of Lemma 8.

Proof. Let $\mathcal{V}(k) = \int_{\theta^o}^{\bar{\theta}} v(\beta^{\lambda}(\cdot; k), \theta) dF^{\lambda}(\theta; k)$. By an integration by parts,

$$\mathcal{V}(k) = v(\beta^{\lambda}(\cdot; k), \bar{\theta}(k)) - v(\beta^{\lambda}(\cdot; k), \theta^o) F^{\lambda}(\theta^o; k) - \int_{\theta^o}^{\bar{\theta}(k)} \frac{d}{d\theta} [v(\beta^{\lambda}(\cdot; k), \theta)] F^{\lambda}(\theta; k) d\theta.$$

Let $k < k'$ and, without loss of generality, let $\beta^{\lambda}(\theta; k) = Y$ for $\theta \in [\bar{\theta}(k), \bar{\theta}(k')]$.²⁵ This implies that $\mathcal{V}(k') \geq \int_{\theta^o}^{\bar{\theta}} v(\beta^{\lambda}(\cdot; k), \theta) dF^{\lambda}(\theta; k')$, and therefore,

$$\mathcal{V}(k') - \mathcal{V}(k) \geq v(\beta^{\lambda}(\cdot; k), \bar{\theta}(k')) - v(\beta^{\lambda}(\cdot; k), \bar{\theta}(k)) \quad (28)$$

$$-v(\beta^{\lambda}(\cdot; k), \theta^o) [F^{\lambda}(\theta^o; k') - F^{\lambda}(\theta^o; k)] \quad (29)$$

$$- \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} \frac{d}{d\theta} [v(\beta^{\lambda}(\cdot; k), \theta)] F^{\lambda}(\theta; k') d\theta \quad (30)$$

$$- \int_{\theta^o}^{\bar{\theta}(k)} \frac{d}{d\theta} [v(\beta^{\lambda}(\cdot; k), \theta)] (F^{\lambda}(\theta; k') - F^{\lambda}(\theta; k)) d\theta. \quad (31)$$

²⁵ $\beta^{\lambda}(\cdot; k)$ is only defined for its domain $[\underline{\theta}, \bar{\theta}(k)]$.

$F^\lambda(\theta^o; k') < F^\lambda(\theta^o; k)$ implies that line (29) is positive. Next, using Lemma 15, $s_\theta(Y, \theta) = u_\theta(Y, \theta)$. Therefore,

$$\begin{aligned}
\text{Line (28)} &= v(\beta^\lambda(\cdot; k), \bar{\theta}(k')) - v(\beta^\lambda(\cdot; k), \bar{\theta}(k)) \\
&= s(Y, \bar{\theta}(k')) - s(Y, \bar{\theta}(k)) - \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} u_\theta(\beta^\lambda(\theta; k), \theta) d\theta \\
&= \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} s_\theta(Y, \theta) d\theta - \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} u_\theta(Y, \theta) d\theta = 0
\end{aligned}$$

$$\begin{aligned}
\text{Line (30)} &= - \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} \frac{d}{d\theta} \left[v(\beta^\lambda(\cdot; k), \theta) \right] F(\theta; k') d\theta \\
&= - \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} \frac{d}{d\theta} \left[s(\underbrace{\beta^\lambda(\theta; k)}_{=Y}, \theta) - \int_{\theta^o}^{\theta} u_\theta(\beta^\lambda(t; k'), t) dt \right] F(\theta; k') d\theta \\
&= - \int_{\bar{\theta}(k)}^{\bar{\theta}(k')} \left[s_\theta(Y, \theta) - u_\theta(\underbrace{\beta^\lambda(\theta; k')}_{=Y}, \theta) \right] F(\theta; k') d\theta = 0.
\end{aligned}$$

Line (31) is strictly positive: $\forall \theta \in [\theta^o, \bar{\theta}(k)]$, $F^\lambda(\theta; k') - F^\lambda(\theta; k) < 0$ and

$$\frac{d}{d\theta} v(\beta^\lambda(\cdot; k), \theta) = s_\beta(\beta^\lambda(\theta; k), \theta) \beta_\theta^\lambda(\theta; k) + \varepsilon_\theta(\beta^\lambda(\theta; k), \theta) [Y - \beta^\lambda(\theta; k)] > 0.$$

Remark 2. Note that these arguments also hold when $\bar{\theta}(k) = \bar{\theta}(k')$, in which case, line (30) is trivially zero. □

Proof of Lemma 9.

Proof. As noted in fn. 20, the principal's total payoff is the total surplus from the relationship. Her period-2 payoff can be expressed as $\int_{\theta^o}^{\bar{\theta}(k)} s(\beta^\lambda(\theta; k), \theta) dF^\lambda(\theta; k) - \lambda R^\lambda(k)$, which, by Lemma 8, is increasing in k . Therefore, if $R^\lambda(k)$ is increasing in k , the period-2

surplus $\int_{\theta^o}^{\bar{\theta}(k)} s\left(\beta^\lambda(\theta; k), \theta\right) dF^\lambda(\theta; k)$ must be increasing in k . Moreover, as noted in the proof of Proposition 3, the period-1 bonus is increasing with the period-2 rent; therefore, if $R^\lambda(k)$ increases with k , then $b^\lambda(k)$ increases with k . Following the notation in fn. 20, analogous to the proof of Proposition 3, it is readily verified that $\bar{s}^n(b)$ and $\bar{s}^o(b; k)$ are both strictly concave and maximized at $b = Y$. This implies that if $b^\lambda(k) < Y$, the period-1 surplus $\lambda \bar{s}^n(b^\lambda(k); k) + (1 - \lambda) \bar{s}^o(b^\lambda(k))$ is increasing in the period-1 bonus. Therefore, it is increasing in k when $R^\lambda(k)$ increases with k . $\square$

Proof of Example 1.

Lemma 17. *If $\hat{\beta}_{\theta k}(\theta; k) \leq 0 \forall \theta, k$, then $R^\lambda(k)$ is strictly increasing in k .*

Proof. By an integration by parts, $R^\lambda(k) = \int_{\theta^o}^{\bar{\theta}(k)} u_\theta\left(\beta^\lambda(\theta; k), \theta\right) [1 - F(\theta; k)] d\theta$. Note that $u_\theta\left(\beta^\lambda(\theta; k), \theta\right)$ is differentiable in θ everywhere except at $T^\lambda(k)$. Define $Q(\theta; k) := \int_\theta^{\bar{\theta}} [1 - F(t; k)] dt > 0$. Doing integration by parts again,

$$\begin{aligned} R^\lambda(k) &= u_\theta\left(\beta^\lambda(\theta; k), \theta\right) Q(\theta; k) \Big|_{\theta^o}^{\bar{\theta}(k)} - \int_{\theta^o}^{\bar{\theta}(k)} \left[\frac{d}{d\theta} u_\theta\left(\beta^\lambda(\theta; k), \theta\right) \right] Q(\theta; k) d\theta \\ &= u_\theta\left(Y, \bar{\theta}(k)\right) Q(\bar{\theta}(k); k) - u_\theta\left(\bar{\beta}^\lambda(k), \theta^o\right) Q(\theta^o; k) \\ &\quad - \int_{T^\lambda(k)}^{\bar{\theta}(k)} \left[\frac{d}{d\theta} u_\theta\left(\hat{\beta}(\theta; k), \theta\right) \right] Q(\theta; k) d\theta - \int_{\theta^o}^{T^\lambda(k)} \left[\frac{d}{d\theta} u_\theta\left(\bar{\beta}^\lambda(k), \theta\right) \right] Q(\theta; k) d\theta. \end{aligned}$$

Differentiating with respect to k now,²⁶

$$\begin{aligned}
& \frac{d}{dk} R^\lambda(k) \\
&= \underbrace{\left[u_{\theta\theta} \left(Y, \bar{\theta}(k) \right) Q(\bar{\theta}(k); k) + u_\theta \left(Y, \bar{\theta}(k) \right) \underbrace{Q_\theta(\bar{\theta}(k); k)}_{=1-F(\bar{\theta}(k); k)=0} - \underbrace{\left[\frac{d}{d\theta} u_\theta \left(\hat{\beta}(\bar{\theta}(k); k), \bar{\theta}(k) \right) \right]}_{=u_{\theta\theta}(Y, \bar{\theta}(k))} Q(\bar{\theta}(k); k) \right] \bar{\theta}'(k)}_{=0} \\
&+ \underbrace{u_\theta \left(Y, \bar{\theta}(k) \right) Q_k(\bar{\theta}(k); k) - u_\theta \left(\ddot{\beta}^\lambda(k), \theta^o \right) Q_k(\theta^o; k)}_{=\text{Term 1}} - \underbrace{\left[\frac{d}{dk} u_\theta \left(\ddot{\beta}^\lambda(k), \theta^o \right) \right] Q(\theta^o; k)}_{<0} \\
&+ \underbrace{\left[\frac{d}{d\theta} u_\theta \left(\hat{\beta} \left(T^\lambda(k); k \right), T^\lambda(k) \right) \right] Q \left(T^\lambda(k); k \right) \cdot T^{\lambda'}(k) - \left[\frac{d}{d\theta} u_\theta \left(\ddot{\beta}^\lambda(k), T^\lambda(k) \right) \right] Q \left(T^\lambda(k); k \right) \cdot T^{\lambda'}(k)}_{=0} \\
&- \underbrace{\int_{T^\lambda(k)}^{\bar{\theta}(k)} \frac{d}{dk} \left(\left[\frac{d}{d\theta} u_\theta \left(\hat{\beta}(\theta; k), \theta \right) \right] Q(\theta; k) \right) d\theta}_{=\text{Term 2}} - \underbrace{\int_{\theta^o}^{T^\lambda(k)} \frac{d}{dk} \left(\left[\frac{d}{d\theta} u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) \right] Q(\theta; k) \right) d\theta}_{=\text{Term 3}}
\end{aligned}$$

Hence $\frac{d}{dk} R^\lambda(k) > (\text{Term 1}) - (\text{Term 2}) - (\text{Term 3})$. Next,

$$\begin{aligned}
\text{Term 1} &= u_\theta \left(\underbrace{\hat{\beta}(\bar{\theta}(k); k)}_{=Y}, \bar{\theta}(k) \right) Q_k(\bar{\theta}(k); k) - u_\theta \left(\underbrace{\hat{\beta} \left(T^\lambda(k); k \right)}_{=\ddot{\beta}^\lambda(k)}, T^\lambda(k) \right) Q_k \left(T^\lambda(k); k \right) \\
&+ u_\theta \left(\ddot{\beta}^\lambda(k), T^\lambda(k) \right) Q_k \left(T^\lambda(k); k \right) - u_\theta \left(\ddot{\beta}^\lambda(k), \theta^o \right) Q_k(\theta^o; k) \\
&= \int_{T^\lambda(k)}^{\bar{\theta}(k)} \frac{d}{d\theta} \left(u_\theta \left(\hat{\beta}(\theta; k), \theta \right) Q_k(\theta; k) \right) d\theta + \int_{\theta^o}^{T^\lambda(k)} \frac{d}{d\theta} \left(u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) Q_k(\theta; k) \right) d\theta \\
&= \int_{T^\lambda(k)}^{\bar{\theta}(k)} \left(\left[\frac{d}{d\theta} u_\theta \left(\hat{\beta}(\theta; k), \theta \right) \right] Q_k(\theta; k) + u_\theta \left(\hat{\beta}(\theta; k), \theta \right) Q_{k\theta}(\theta; k) \right) d\theta \\
&+ \int_{\theta^o}^{T^\lambda(k)} \left(\left[\frac{d}{d\theta} u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) \right] Q_k(\theta; k) + u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) Q_{k\theta}(\theta; k) \right) d\theta
\end{aligned}$$

²⁶Note that the derivative of R^λ exists almost everywhere.

and

$$\begin{aligned}
\text{Term 2} &= \int_{T^\lambda(k)}^{\bar{\theta}(k)} \left[\frac{d}{d\theta} u_\theta \left(\hat{\beta}(\theta; k), \theta \right) \right] Q_k(\theta; k) d\theta + \int_{T^\lambda(k)}^{\bar{\theta}(k)} \left[\frac{d^2}{d\theta dk} u_\theta \left(\hat{\beta}(\theta; k), \theta \right) \right] Q(\theta; k) d\theta \\
\text{Term 3} &= \int_{\theta^o}^{T^\lambda(k)} \left[\frac{d}{d\theta} u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) \right] Q_k(\theta; k) d\theta + \int_{\theta^o}^{T^\lambda(k)} \left[\frac{d^2}{d\theta dk} u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) \right] Q(\theta; k) d\theta
\end{aligned}$$

Therefore,

$$\begin{aligned}
& (\text{Term 1}) - (\text{Term 2}) - (\text{Term 3}) \\
&= \int_{T^\lambda(k)}^{\bar{\theta}(k)} u_\theta \left(\hat{\beta}(\theta; k), \theta \right) Q_{k\theta}(\theta; k) d\theta + \int_{\theta^o}^{T^\lambda(k)} u_\theta \left(\ddot{\beta}^\lambda(k), \theta \right) Q_{k\theta}(\theta; k) d\theta \\
&\quad - \int_{T^\lambda(k)}^{\bar{\theta}(k)} \underbrace{\left[u_{\theta\beta\beta} \left(\hat{\beta}(\theta; k), \theta \right) \hat{\beta}_\theta(\theta; k) \hat{\beta}_k(\theta; k) + u_{\theta\beta} \left(\hat{\beta}(\theta; k), \theta \right) \hat{\beta}_{\theta k}(\theta; k) + u_{\theta\theta\beta} \left(\hat{\beta}(\theta; k), \theta \right) \hat{\beta}_k(\theta; k) \right]}_{=u_{\theta\theta k}(\hat{\beta}(\theta; k), \theta)} Q(\theta; k) d\theta \\
&\quad - \int_{\theta^o}^{T^\lambda(k)} \underbrace{\left[u_{\theta\theta\beta} \left(\ddot{\beta}^\lambda(k), \theta \right) \ddot{\beta}^{\lambda'}(k) \right]}_{=u_{\theta\theta k}(\ddot{\beta}^\lambda(k), \theta)} Q(\theta; k) d\theta
\end{aligned}$$

Since $Q_{k\theta}(\theta; k) = -F_k(\theta; k) > 0$, the first line is positive. From the proof of Lemma 2, $u_{\theta\beta} > 0$, and it is readily verified that $u_{\theta\theta\beta}, u_{\theta\beta\beta} > 0$; from Lemma 7, $\frac{d\ddot{\beta}^\lambda(k)}{dk} < 0$. Therefore, the last line is positive. If $\hat{\beta}_{\theta k}(\theta; k) \leq 0$, then the second line is also positive. This in turn implies that $\frac{dR^\lambda(k)}{dk} > 0$. $\square$

The claim in Example 1 is established by checking that the condition $\hat{\beta}_{\theta k}(\theta; k) \leq 0$ holds under the given parametrization.

Proof. When $\psi(x) = \xi x^2$, it is readily verified that $\varepsilon(\beta, \theta) = \frac{1}{2\xi} \beta \theta^2$. From (9), $\hat{\beta}(\theta) = \frac{\theta Y}{2H(\theta) + \theta}$. Under the family of uniform distributions, $H(\theta; k) = k - \theta$. Therefore, $\hat{\beta}(\theta; k) = \frac{\theta}{2k - \theta} Y$ and it is immediate that $\hat{\beta}_{\theta k}(\theta; k) < 0$. $\square$

Proof of Proposition 6.

Proof. Consider program $(\mathcal{P})$. For any $\lambda \in (0, 1]$, the following menu of period-2 contracts is always feasible: $\forall \theta \in [\theta^o, \bar{\theta}]$, $\beta(\theta^o) = Y$ and $\alpha(\theta) = -s(Y, \theta^o)$, which gives a value of $s(Y, \theta^o)$. Since the value of program $(\mathcal{P})$ can be written as $\int_{\theta^o}^{\bar{\theta}} s(\beta^\lambda(\theta), \theta) dF^\lambda(\theta) - \lambda R^\lambda$ and its solution is unique, this implies that

$$\int_{\theta^o}^{\bar{\theta}} s(\beta^\lambda(\theta), \theta) dF^\lambda(\theta) - s(Y, \theta^o) > \lambda R^\lambda. \quad (32)$$

Note that $S(\theta) = s(Y, \theta)$. Let $\bar{s}^o(b) = e^o(b)Y - \psi\left(\frac{e^o(b)}{\theta^o}\right)$ and $\bar{s}^n(b) = e^n(b)Y - E\left[\psi\left(\frac{e^n(b)}{\theta^n}\right)\right]$. From (15), $R^\lambda \geq \bar{W}^o(b^\lambda) - \bar{W}^n(b^\lambda)$; therefore, if $b^\lambda = Y$, then

$$R^\lambda \geq \bar{W}^o(Y) - \bar{W}^n(Y) = \bar{s}^o(Y) - \bar{s}^n(Y),$$

which implies that

$$\begin{aligned} \lambda R^\lambda &\geq \lambda(\bar{s}^o(Y) - \bar{s}^n(Y)) \\ &= \bar{s}^o(Y) - [\bar{s}^o(Y) + \lambda(\bar{s}^n(Y) - \bar{s}^o(Y))] \end{aligned} \quad (33)$$

(32) and (33) jointly imply that

$$\int_{\theta^o}^{\bar{\theta}} s(\beta^\lambda(\theta), \theta) dF^\lambda(\theta) + \lambda \bar{s}^n(Y) + (1 - \lambda) \bar{s}^o(Y) \geq s(Y, \theta^o) + \bar{s}^o(Y) = S^{exploit},$$

where the left-hand side is the total surplus—hence, the principal's total payoff—from exploration with probability λ . $\square$

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