TECHNICAL CHANGE, MORAL HAZARD, AND THE DECENTRALIZATION PENALTY

Thomas Marschak[†] and Dong Wei[††]

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We consider two modes of organizing a firm and we compare them with regard to social welfare. In the Centralized mode, worker-control techniques, together with adequate compensation, ensure that the worker chooses a surplus-maximizing effort. In the Decentralized mode the worker is not controlled. Instead a profit-driven Principal contracts with a self-interested Agent (worker) who freely chooses an effort and bears its cost. The Principal rewards the Agent once she sees the revenue generated by the Agent's hidden choice. The loss of surplus when the Principal induces her favorite effort is called the *Decentralization Penalty*. For certain common contract types, we study the behavior of the Penalty in response to changes in production technology. We find that as production technology improves, the Penalty oscillates. It follows a continuous-rise-sudden-change cycle. Under reasonable assumptions on costs and expected revenues, the sudden change must be a drop. While advances in worker-control technology always strengthen the social-welfare case for the Centralized mode, advances in production technology may do the opposite.

† Haas School of Business, University of California, Berkeley.
†† Department of Economics, University of California, Santa Cruz.

1. Introduction.

How does the rapid stream of technical advances that we currently see affect the best way to organize a firm? Many advances fit the traditional model: they increase the quantity produced by a unit of workers' effort (for given capital) and so they decrease the cost of every product quantity. We shall call them advances in *production* technology. But advances may also be of a novel type: they make it easier for a firm to influence a worker's choice of effort and they reduce the cost of ensuring that a worker selects the effort the firm desires. Those advances include devices and techniques that instantly track worker's activities, convey quick instructions from remote locations, and compile detailed worker histories. We shall call them advances in the technology of *control*.[1]

The effect of both technical advances on the best organization of firms is a complex question. It is natural to start with the simplest models. Here we study a highly simplified one-worker firm in which the worker's effort produces one of several possible *revenues*. For a given effort, the resulting revenue is uncertain, but the probability of each revenue is common knowledge. There is a set of possible efforts, each effort has a cost, and advances in production technology lower that cost. Advances in production technology and in control technology are external to the firm.

We consider two ways of organizing the firm, which we shall call the *Centralized* mode and the *Decentralized* mode. In the Centralized mode the worker chooses whatever effort the firm selects. The worker does so because the firm uses effective control devices and techniques. The worker may find them unpleasant but will accept them if given sufficient compensation. What worker effort does the firm select in the Centralized mode? We shall assume it to be an effort that maximizes *surplus*. The surplus achieved by a given effort is the expected revenue generated by the effort minus the effort's cost. A Centralized firm maximizes surplus if it wants to satisfy the makers of public policy. The firm, might, for example, be regulated. It might propose one of the two modes to the regulator, who judges each mode from the social-welfare point of view.[2] In judging the Centralized mode, the regulator considers not only maximal surplus — which the firm achieves by using control devices and techniques — but also the cost of those devices and techniques and the compensation that the controlled worker requires.

In the Decentralized mode there are no controls. Instead the firm faces moral hazard. The worker, whom we now call the Agent, pays the cost of the effort he freely chooses but is rewarded

[1] Recent surveys of such devices and techniques include West (2021), Ball (2010); Findlay and McKinlay (2003); Oliver (2002); Mason, *et al* (2002); Moore *et al* (2018); Perez-Zapata *et al* (2016); Warin and McCann (2018); Mateescu and Nguyen (2019). Legal aspects are surveyed in Ajunwa, Crawford, and Schultz (2017), Tippet (2017), and Vagle (2020). Zuboff (2019) studies the limits on workplace surveillance imposed by political and legal institutions. Organizational surveillance is studied from a social psychology point of view in Sewell and Barker (2006) and in many of the references they provide. A specific example of sophisticated worker control may be the "fulfillment centers" of Amazon. Here we have to rely, for the present, on accounts by various journalists: "The human costs of Amazon's employment machine", *New York Times*, June 15, 2021; "I worked at an Amazon fulfillment center; they treat workers like robots", TIME, July 18,2019; "How Amazon automatically tracks and fires workers for 'productivity' ", Colin Lecher, *The Verge*, August 25, 2019; "The big issue for Amazon workers isn't money, it's autonomy", *Quartz at Work*, April 14, 2021.

[2] In Section 6.2 we briefly consider another way to judge the two modes. They are judged from the point of view of an "owner", who seeks maximum profit.

by a Principal. The Agent's effort choice is hidden until revenue is realized. Once the Principal sees the revenue, she pays the Agent a non-negative amount. The payment is specified in a contract which the Principal proposes and the Agent accepts. We shall be particularly interested in *bonus* contracts, where a positive payment is only made to the Agent when the highest revenue is realized, and in *fixed-share* contracts, where the payment is a fixed share of the realized revenue. The Agent is risk-neutral. He chooses the effort which maximizes his net gain — his expected payment minus the effort's cost. The Principal is also risk-neutral and her net gain for a given contract is expected revenue minus the expected value of her payment to the Agent. She uses a contract for which the induced effort maximizes her net gain. The social-welfare measure of the Decentralized mode — the measure that the public-policy judge uses — is the surplus achieved by the induced effort. We call it *Decentralized surplus.*

We now specify more precisely the social-welfare measure which the public-policy judge uses in judging the Centralized mode. Let $K > 0$ be the "social cost" of the firm's control devices and techniques. It is the sum of (1) the cost of the control devices and techniques that the firm uses, and (2) the compensation which the worker requires if he is going to accept the unpleasantness of the controlled workplace. To evaluate the Centralized mode, the judge asks: "*given* that the firm uses control devices and techniques, which enable it to direct the worker's effort, what effort maximizes social welfare?" The answer is: an effort that maximizes surplus. So if the firm wants the judge to favor the Centralized mode, it must specify that in that mode it will use its control capability to ensure that the worker's effort is indeed surplus-maximizing. Then the judge, when comparing the two modes, will use

$$\text{(maximal surplus)} - K$$

as the social-welfare measure of the Centralized mode.

Note that as control technology advances, fewer resources, and perhaps less compensation, are needed, so K drops. But we assume, as already noted, that such advances are external to the firm; the firm plays no role in achieving them. Control technology is given to the firm and does not change. Production technology is also assumed to be external to the firm, but — in our analysis — it *does* change. When we say "a change in production technology strengthens (weakens) the social-welfare case for the Centralized mode", we mean that the change increases (decreases)

$$[\text{maximal surplus - } K] \; - \; [\text{Decentralized surplus}].$$

That brings us to the Decentralization Penalty, our main concern. The Penalty is the amount by which maximal surplus, achieved in the Centralized mode, exceeds the surplus attained in the Decentralized mode. When production technology advances, the cost of every effort drops. Our primary agenda is to characterize the way the Penalty behaves when those advances occur. As we noted, the social-welfare measure of the Centralized mode is maximal surplus minus K, the social cost of control. Hence:

> The Centralized mode is welfare-superior (welfare-inferior) to the Decentralized mode if the Penalty exceeds (is less than) K.

We can rephrase our question in the standard language of Principal/Agent theory: when does a drop in the cost of effort increase (decrease) the welfare loss due to the Agent's "second-best" effort choice? Papers which focus on this question appear to be quite scarce, even though the Principal/Agent literature is voluminous.

We shall not attempt to derive K, the social cost of control, by modeling control technology in detail and studying, in a formal way, workers' tradeoff between compensation and the unpleasantness of control.[3] Nor will we pursue the variations found in the extensive literature on costly monitoring. There increasing the effectiveness of monitoring lowers the pay required to induce a given effort and a balance has to be struck between the cost of increasing that effectiveness and the saving in pay. [4] We will see that finding the behavior of the Decentralization Penalty when production technology changes is quite challenging, even though our one-worker model is extremely simple. So we defer the complications.

Related literature.

The paper closest to ours is Balmaceda *et al* (2016). That paper concerns the moral-hazard model that we consider here, but it studies the *ratio* of the maximal surplus to the surplus when the Principal induces her favorite effort, rather than the difference between the two. Computer scientists and others have called that ratio "the price of anarchy."[5] The main aim in Balmaceda *et al* is to find a useful upper bound to the ratio. Under the assumptions made, the number of efforts turns out to be a tight upper bound. (But the effect of effort-cost reduction on the ratio is not examined). Balmaceda *et al* is also relevant to our study because we shall pay particular attention to a Principal who uses bonus contracts. Balmaceda *et al* show that the Principal loses nothing by confining attention to such contracts if the revenue distribution satisfies the Monotone Likelihood Ratio condition with respect to effort level, which we shall assume, as well as a condition called "Increasing Marginal Cost of Probability" (IMCP), which we shall *not* assume.[6]

In our setting, it is natural to use the difference between maximal surplus and Decentralized surplus in defining the Decentralization Penalty rather than the ratio considered in Balmaceda *et al*. That allows us to measure welfare in the Centralized mode as maximal surplus *minus* the cost of control.

Schmitz (2005) considers an Agent who can choose any effort in the interval $[0, 1]$. The resulting revenue (in our terminology) can be High or Low, with probabilities that are common

[3]A recent paper (Ashkenazy (2021)) studies this tradeoff in a formal model of a one-worker firm. The firm divides its capital into two parts. One of them, combined with worker effort, yields a product quantity specified by a shifting production function. The other is used to influence the worker, by imposing an unpleasant "job strain". The worker's effort depends on the job strain and the payment he receives.

[4]Among the papers that study costly monitoring are Algulin and Ellingsen (2002), Schwartz and Watson (2004), Chakravarty and MacLeod (2009), and Kvaloy and Olsen (2016).

[5]For other research related to the price of anarchy, see, e.g., Roughgarden (2005),Nissan, Roughgarden, Tardos, and Vazirani (eds.) (2007), and Moulin (2008).

[6]IMCP requires that the marginal cost of raising the probability of the highest revenue is an increasing function of effort. We provide further details in Section 4.

knowledge. The Agent is rewarded by a Principal once revenue is realized. But if the Principal spends money on a surveillance device, then the Agent's effort choice becomes observable and the Agent is rewarded (or punished) when the choice is made. It is shown that if the surveillance cost is sufficiently high, then welfare increases if the device is banned. Another model related to ours is studied in Acemoglu and Wolinsky (2011). The novelty of their model is that the Agent is punished if he refuses to participate and leaves. So there is a family of organizational modes rather than our two modes; each mode corresponds to a possible punishment level.[7] An alternative Principal/Agent model of coercion is studied in Chwe (1990).

There is an abundant literature on decentralization in firms and other organizations where the costs of communication, information processing, and other cognitive activities play a major role (Surveys include Mookherjee (2006), Marschak (2006), Garicano and Prat (2011)). Often there is a "manager" and several agents who choose actions based on limited information about a changing external world. Those actions, together with the external state, yield a payoff. Controlling the actions may requite costly communication, but may yield higher net payoffs than the self-interested actions that are chosen in the absence of control.[8] Such models are far more complex than the one we study. Tracing the effect of technical change on the performance of alternative organizational forms is an ambitious agenda. It is rarely pursued.

Several papers study models that may explain real data about the autonomy granted to subordinates in a group of observed firms. In Acemoglu *et al* (2006) there is an advancing technology frontier, and autonomous managers respond by adopting or rejecting the new technology. The empirical question is whether the autonomous managers turn out to be more productive than the others. In Christie *et al* (2003), survey data that reflect "knowledge transfer costs", and "control costs" for a group of firms are examined. Hypotheses about the influence of these variables on another observed variable, called "decentralization", are tested. The paper, however, does not suggest a model of Principal/Agent behavior that might explain the observed results. In Widener *et al* (2008) data obtained from interviews with a collection of Internet firms are used to test hypotheses about the relation of surveillance activities to organizational performance.

As we have already noted, our central question can be rephrased in standard Principal/Agent language: what is the effect of effort-cost reduction (following a technical improvement) on the welfare loss due to the Agent's "second-best" choices? Starting with the earliest Principal/Agent papers, we find models where the Agent's effort may have a cost. The Agent has a utility function on her actions and rewards. Agent utility for the action a and the reward y takes the form $V(y) - g(a)$. Among the early papers where this occurs are Holmstrom (1979), (1982) and Grossman and Hart (1983). The action a might be effort and $g(a)$ could be its cost. Welfare

[7]One interpretation of the model is slavery, and that is indeed the focus of the paper. It is shown that increasing the exit punishment (or lowering the cost of a given punishment level) reduces welfare. There are just two revenues and the set of possible efforts is the inteval $[0, 1]$.

[8]Among the papers that study questions of this sort are Melumad *et al* (1995), Aghion and Tirole (1997), and Dessein (2002). In some of the efficiency-wage models (see, for example, Akerlof and Yellen, 1986) the worker's effort is an increasing function of his wage, a balance is struck between the chosen wage and the revenue generated by the chosen effort, and controls are not needed. Akerlof and Kranton (2005) surveys the role of identity in creating organizational loyalty without controls; establishing an identity may have costs.

loss also appears very early in the literature. Ross (1973), for example, finds conditions under which the solution to the Principal's problem maximizes welfare (as measured by the sum of Agent's utility and Principal's utility) and notes that these conditions are very strong. In both the early literature, and the abundant literature that followed it, papers whose main concern is the relation between effort cost and welfare loss are hard to find.

The remainder of the paper.

The remaining material is organized as follows. Section 2 states the model formally. Section 3 establishes some basic propositions about surplus-maximizing effort, the "Principal-favorite" effort, maximal surplus, and Decentralized surplus. Section 4 considers bonus contracts and shows how the Penalty behaves as technology changes. In 4.3 we show that if there are only two efforts, then IMPC is both necessary and sufficient for the Principal to lose nothing by confining attention to bonus contracts. Section 5 considers fixed-share contracts and again characterizes the behavior of the Penalty. Section 6 considers some variations. Section 7 presents some economic examples. Section 8 concludes. An Appendix provides proofs.

2. The Model

There is one risk-neutral worker. He has a set of possible efforts. Here we face a sharp modeling choice. In many moral-hazard papers the set is finite (often there are just two efforts). In others the set is a continuum, often an interval. The analytic techniques needed are different for each choice. The finite case may be more realistic than a continuous-effort model in which surplus-maximizing effort and the Principal's effort change continuously as production technology advances. (We briefly illustrate a continuous-effort model in Section 6.3). Our finite-effort model allows for sudden breakthroughs in production technology which cause the Principal's chosen effort, and hence the Penalty, to jump. We show (in Proposition 1) that under reasonable conditions on costs and expected revenues any jump in the Penalty as production technology advances must be downward. So the social-welfare case for the Decentralized mode is always strengthened by the breakthrough.

There are $E \geq 2$ possible efforts. They are denoted $1, 2, \ldots, e, \ldots, E$, where each is higher than its predecessor. The cost of effort e is tC_e, where $C_e > 0$ and $t > 0$. C_e is strictly increasing in e, and $t > 0$ is a parameter which drops when production technology improves. There are $S \geq 2$ possible revenues, denoted $R_1, R_2, \ldots, R_S$, where $0 \leq R_1 < R_2 < \cdots < R_S$. The probability distribution of revenue depends on the effort chosen. When effort e is chosen, the probability that revenue will turn out to be R_s is p_s^e. We let p^e denote the vector $(p_1^e, \ldots, p_S^e)$. So our problem is defined by the triple $(\{C_e\}_{e=1,\ldots,E}\ ,\ \{R_s\}_{s=1,\ldots,S}\ ,\ \{p^e\}_{e=1,\ldots,E})$.

For effort e, we let $\overline{R}^e$ denote the average revenue (i.e., $\overline{R}^e = \sum_{s=1}^S\ p_s^e R_s$). Then surplus, at the effort e and the production technology defined by t, is $\overline{R}^e - tC_e$.

As is common in the moral-hazard literature, we shall assume that the revenue distributions have the *Monotone-Likelihood-Ratio (MLR)* property.

Definition 1

The probabilities $\{(p_1^e, \ldots, p_S^e)\}_{e=1,\ldots,E}$ have the Monotone Likelihood Ratio (MLR) property if

$$\frac{p_{s^*}^e}{p_s^e} > \frac{p_{s^*}^f}{p_s^f} \text{ whenever } e > f, s^* > s.$$

Informally: when effort increases, so does the ratio of the probability that we will see a given revenue to the probability that we will see a lower one. MLR implies that if $e > f$, the cumulative distribution function of revenue for the effort e first-order stochastically dominates the cumulative distribution function for the effort f. Consequently

- Expected revenue strictly increases when effort increases;
- The probability p_S^e of the highest revenue R_S strictly increases when effort increases.

Note that there may be more than one surplus-maximizing effort. We shall make use of a second condition, which restricts the way surplus behaves when effort increases.

Definition 2

The triple $(\{C_e\}_{e=1,\ldots,E}\ ,\ \{R_s\}_{s=1,\ldots,S}\ ,\ \{p^e\}_{e=1,\ldots,E})$ has the *Approximate-concavity* property if for every $t > 0$, the piecewise-linear function of e that we obtain when we connect the E points

$$(1, \overline{R}^1 - tC_1), (2, \overline{R}^2 - tC_2), \ldots, (e, \overline{R}^e - tC_e), \ldots, (E, \overline{R}^E - tC_E)$$

is non-constant and concave.

If this condition holds,[9] we have the following pattern: as the effort e rises above $e = 1$, surplus strictly rises until it reaches its maximum, where it may stay for a while as effort increases a bit further; after that it may descend. Notice that if Approximate-concavity holds, then the following holds for any fixed t: *if two efforts are less than the smallest maximizer of surplus, then surplus is less at the smaller of those two efforts; if two efforts exceed the largest maximizer, then surplus is less at the larger of those two efforts.* The first of those two statements will turn out to be very useful. Here is an informal rephrasing of the first statement: *we diminish surplus whenever we increase the amount by which effort falls short of the lowest surplus-maximizing effort.*[10]

[9] If t is sufficiently large, surplus will be negative at every effort. Then Approximate-concavity means that surplus descends as effort increases, and it descends at an increasing rate. Our main application of Approximate-concavity occurs in the proof of Proposition 1 below, which characterizes the behavior of the Penalty as t changes. For large t, the Penalty is zero, because then both a surplus-maximizer and the Principal choose the lowest effort. In showing this, Approximate-concavity is not needed.

[10] If we let the efforts be product quantities, then the Approximate-concavity condition approximately fits a conventional model of the firm. In that model, (1) cost is convex (marginal cost rises); (2) revenue is concave (marginal revenue falls or, in the case of a price-taker, stays constant); and so (3) profit is concave (it rises and

A *contract* $w = (w_1, \ldots, w_S)$ states that the Agent receives the *wage* $w_s \geq 0$ if revenue turns out to be R_s. We shall say that a contract w, chosen by the Principal, *induces* the effort e as long as it satisfies the usual Individual Rationality (IR) and Incentive-compatibility (IC) conditions for that effort. That means we will see the Agent choosing that effort even if it gives him the same net gain as some other effort. Thus we make the conventional assumption that if there is such a tie, then the Agent breaks it in favor of the effort the Principal desires.

We let $\overline{w}^e$ denote the average wage received by the Agent when the effort is e. So $\overline{w}^e = \sum_{s=1}^{S} p_s^e w_s$. The Principal, like the Agent, is risk-neutral. Accordingly we informally say that a contract w which induces e *costs* the Principal $\overline{w}^e$. There may be many contracts that induce e. Among them the Principal seeks a contract that is cheapest. To find it, she solves a linear-programming problem which we shall call *the optimally-induce-e problem*:

Find a vector $w = (w_1, \ldots, w_S)$ of nonnegative wages which minimizes $\overline{w}^e$ subject to:

- $\overline{w}^e \geq tC_e$ (IR)
- $\overline{w}^e - tC_e \geq \overline{w}^f - tC_f$ for all $f \neq e$. (IC)

We have no interest in efforts that cannot be optimally induced. So henceforth *we restrict attention — without further comment — to triples* $\left(\{C_e\}_{e=1,\ldots,E}\ ,\ \{R_s\}_{s=1,\ldots,S}\ ,\ \{p^e\}_{e=1,\ldots,E}\right)$ *which have the property that for every effort e, the optimally-induce-e problem has a solution.*

If w solves the optimally-induce-e problem for a given t, then we let the symbol $A_e(t)$ denote the average wage $\overline{w}^e$. So $A_e(t)$ is the lowest cost of inducing e. The Principal (weakly) prefers the effort e to the effort f if her net gain is not lower for e, i.e., $\overline{R}^e - A_e(t) \geq \overline{R}^f - A_f(t)$. We now formally define the two efforts which we sketched in the Introduction. One of them is the surplus-maximizing effort. The other is the Principal-favorite effort.

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then falls). Consider the piecewise-linear function on $[1, E]$ which connects the E costs

$$tC_1, \ldots, tC_e, \ldots, tC_E.$$

If we approximate the conventional assumption, we require that piecewise-linear function to be convex. Consider also the piecewise-linear function on $[1, E]$ which connects the E expected revenues

$$\overline{R}^1, \ldots, \overline{R}^e, \ldots, \overline{R}^E.$$

If we approximate the conventional assumption, we require that piecewise-linear function to be concave. Finally consider the piecewise-linear function on $[1, E]$ which connects the E "profits"

$$\overline{R}^1 - tC_1, \ldots, \overline{R}^e - tC_e, \ldots, \overline{R}^E - tC_E.$$

If we approximate the conventional assumption, we require that piecewise-linear function to be concave.

But we get a concave function on a given interval whenever we subtract a convex function on that interval from a concave function on the interval. (That holds whether or not those functions are differentiable). So the piecewise-linear "profit" function is concave on the interval $[1, E]$, which is exactly what Approximate-concavity requires.

Definition 3

For a given t, we let $\gamma(t)$ denote the **largest surplus-maximizing effort**. It is the largest element in the set

$$\text{argmax}_{e\in\{1,\ldots,E\}}\left[\overline{R}^{e}-tC_e\right].$$

We let $\delta(t)$ denote the **Principal-favorite effort**. It is the largest element in the set

$$\text{argmax}_{e\in\{1,\ldots,E\}}\left[\overline{R}^{e}-A_e(t)\right].$$

Note that the functions $\gamma(\cdot),\delta(\cdot)$ are (integer-valued) step functions. Each takes at most E values. Note also that ties, if any, are *broken upward*.

The *Decentralization Penalty*, denoted $D(t)$, is the difference between maximal surplus and the surplus in the Decentralized mode under the Principal-favorite effort. So

$$D(t)=[\overline{R}^{\gamma(t)}-tC_{\gamma(t)}]-[\overline{R}^{\delta(t)}-tC_{\delta(t)}]=[\overline{R}^{\gamma(t)}-\overline{R}^{\delta(t)}]+t\cdot\left(C_{\delta(t)}-C_{\gamma(t)}\right). \tag{1}$$

The Penalty formula at the right of the second equality will be particularly useful. Note that the Penalty is never negative. (If it were positive, $\gamma(t)$ would not be a surplus maximizer). The penalty equals zero if the surplus-maximizer and the Principal "agree", i.e., $\gamma(t)=\delta(t)$. The behavior of the function $D(\cdot)$ is our main concern.

3. Basic Properties of the Decentralization Penalty

In this section we establish two basic properties of optimal efforts and the Decentralization Penalty. Those properties will be useful in the subsequent analysis.

3.1 Monotonicity of surplus-maximizing and Principal-Favorite Efforts

When production is less costly, it becomes cheaper to induce the worker to choose a higher effort. Consequently, the surplus-maximizing and Principal-favorite efforts rise with technological improvement. That is established in the following Lemma.

Lemma 1

If $t_L<t_H$, then $\gamma(t_L)\geq\gamma(t_H)$ and $\delta(t_L)\geq\delta(t_H)$.

The inequality concerning the surplus-maximizing effort $\gamma(\cdot)$ is easy to prove. We have to rule out an effort pair (e,f) for which the following holds: (i) e maximizes surplus at $t=t_H$; (ii) f maximizes surplus at $t=t_L$; and (iii) $e>f$. If we had such a pair (e,f), then, in particular, we would have (because of (i)):

at t_H, the surplus at f is weakly lower than the surplus at e,

i.e.,

$$t_H\cdot(C_e-C_f)\leq e-f.$$

Hence, since $t_L < t_H$, $e > f$, and $C_e > C_f$ (using (iii)), we have

$$t_L \cdot (C_e - C_f) < e - f.$$

So, at t_L, surplus at e is strictly higher than surplus at f. That contradicts (ii). So the pair (e, f) cannot exist and the proposition is established.

The inequality that concerns the Principal-favorite effort $\delta(\cdot)$ is of interest in itself. It says that a technical advance never leads the Principal to induce less effort from the Agent. Its proof in the Appendix exploits the Strong Duality theorem of linear programming.[11]

3.2 Squandering and the Decentralization Penalty

It is traditional to say that the Principal (and the Agent) *shirks* if the effort chosen is less than the surplus-maximizing effort. We use the term *squanders* when the reverse is true. So the Principal *squanders at t* if $\delta(t) > \gamma(t)$. Recall the definition of the Decentralization Penalty in (1). Since C_e is strictly increasing in e, the following must hold:

Lemma 2

Suppose that the step functions $\gamma(\cdot)$ and $\delta(\cdot)$ are constant throughout an interval, i.e., there exist γ', δ' such that $\gamma(t) = \gamma', \delta(t) = \delta'$ at all t in the interval. Then in that interval D is strictly decreasing if $\delta' < \gamma'$ (no squandering), strictly increasing if $\delta' > \gamma'$ (squandering), and zero if $\delta' = \gamma'$.

Any interval on which the step functions $\gamma(\cdot)$ and $\delta(\cdot)$ are not equal has a subinterval where each is constant. So Lemma 2 will be an important tool in characterizing the behavior of the Penalty. Suppose we graph the Penalty, with t on the horizontal axis, and we move from right to left, i.e., technology improves. Examining the second Penalty formula in (1), we see that if there is no squandering, then an interval where the Penalty continuously changes while $\gamma(\cdot), \delta(\cdot)$ are constant must be an interval where the Penalty continuously *falls*. We shall see that bonus contracts and fixed-share contracts, studied in the next two sections, have the "no-squandering" property.

4. Bonus Contracts

It is common practice to pay a worker a fixed amount and to add a bonus that depends on the observed result of the worker's unobserved effort. The term "bonus" appears often in the moral-hazard literature.[12] In our setting, we shall call a contract $w = (w_1, \ldots, w_S)$ a *bonus contract* if it has the form $(0, \ldots, 0, z)$, where $z > 0$. The Agent receives a fixed amount (normalized at zero) regardless of revenue and is rewarded with a positive bonus when revenue turns out to be R_S,

[11] Here our modeling of technical advance as a shift in the the *multiplicative* parameter t turns out to be very helpful. When we write the maximand in the dual of the Principal's optimally-induce-e problem, we find that t "factors out": the maximand equals t times an expression that involves only the dual "shadow prices" and the functions C_e. That is a key part of the proof.

[12] For example, Herweg *et al* (2010) use the word "bonus" to describe a contract where the Agent receives a lump sum if a certain level of performance is reached. In papers where there are just two possible outcomes (e.g., Halac *et al* (2016), Fong and Li (2016)), the reward for a "success" may be labeled a "bonus". It appears, however, that there is no standard definition of the term.

the highest possible revenue. In this section, we characterize the behavior of the Decentralization Penalty under bonus contracts.

Before proceeding we ask whether the restriction to bonus contracts reduces the Principal's net gain. As previously noted, Balmaceda *et al* introduce a condition on the effort costs and the revenue distribution which they call Increasing Marginal Cost of Probability (IMCP). To understand this condition, recall that MLR implies that the probability of the highest revenue R_S is strictly increasing in effort. IMCP concerns the ratio of the marginal cost of exerting a higher effort to the resulting increase in the probability of R_S. We let v_e denote the ratio. The IMCP condition requires that v_e be weakly increasing in e.[13] That happens, for example, if the marginal cost of effort is weakly increasing and there are decreasing marginal returns to effort in the following sense: the improvement in the probability of the highest revenue when effort moves one level higher decreases with effort.[14] Balmaceda *et al* show (in their Proposition 1) that if IMCP is satisfied, then the bonus contract $(0, \ldots, 0, v_e)$ induces the effort e and costs the Principal no more than any other contract that also induces e. So the Principal loses nothing if she confines attention to bonus contracts. [15] We shall *not*, however, assume IMCP. We do not need that assumption in order to obtain our main result (Proposition 1) about the behavior of the Decentralization Penalty when bonus contracts are required.

4.1 Inducing an Effort with a Bonus Contract

We shall say that a contract $(0, \ldots, 0, z)$ *bonus-induces* an effort e if it satisfies the IR and IC conditions. We shall say that the contract *optimally* bonus-induces e if it bonus-induces e and does so at least as cheaply as any other contract which bonus-induces e. To find a contract which optimally bonus-induces a given effort, say e, the Principal solves a linear programming problem which is simpler than the optimally-induce-e problem when contracts are unrestricted. The new problem is:

Find a nonnegative z which minimizes $p_S^e z$ subject to:

- $p_S^e z \geq tC_e$ (IR)
- $p_S^e z - tC_e \geq p_S^f z - tC_f$ for all $f \neq e$. (IC)

Let $z^e(t)$ denote a solution. We shall say that e is *optimally bonus-induced* by the contract $z^e(t)$. We confine attention to triples $\left(\{C_e\}_{e=1,\ldots,E}, \{R_s\}_{s=1,\ldots,S}, \{p^e\}_{e=1,\ldots,E}\right)$ where each of the E possible efforts can be optimally bonus-induced (the linear programming problem always has a solution). Let $A_e^b(t)$ denote $p_S^e z^e(t)$. It costs the Principal $A_e^b(t)$ to optimally bonus-induce the effort e.

[13] Formally, define $v_1 \equiv \dfrac{C_1}{p_1^S}$ and $v_e \equiv \dfrac{C_e - C_{e-1}}{p_S^e - p_S^{e-1}}$ for $2 \leq e \leq E$. IMCP says that $v_1 \leq v_2 \leq \cdots \leq v_E$.

[14] Balmaceda *et al* point out that IMCP is weaker than the well-known "convexity of the distribution function condition" which is often used to validate the first-order approach in the continuous-effort case.

[15] In our setting the Balmaceda *et al* result means that for any $t > 0$ the Principal loses nothing by confining attention to contracts which have the form $(0, \ldots, 0, tv_e)$.

Can it cost the Principal *less* to induce a higher effort? For bonus contracts this cannot happen.[16] To see this, suppose that $f > e$. To bonus-induce effort f, the solution $z^f(t)$ to the linear programming problem must satisfy the "f-is-not-worse-than-e" IC condition, which can be written

$$z^f(t) \geq t \cdot \frac{C_f - C_e}{p_S^f - p_S^e},$$

where $p_S^f - p_S^e > 0$, because of MLR. On the other hand, to bonus-induce effort e, the solution $z^e(t)$ must satisfy the "e-is-not-worse-than-f" IC condition, which can be written

$$z^e(t) \leq t \cdot \frac{C_f - C_e}{p_S^f - p_S^e}.$$

So we have

$$\text{if } f > e, \text{ then } z^f(t) \geq z^e(t) \text{ and } A_f^b(t) \geq A_e^b(t). \tag{2}$$

For brevity, we slightly abuse the symbol δ. We now use $\delta(t)$ to denote the *Principal-favorite effort at t under bonus contracts*. That is defined as the largest member of the set

$$\text{argmax}_{e \in \{1,\ldots,E\}} \left[\overline{R}^e - A_e^b(t)\right].$$

So, as in Definition 3, ties are broken upward. As before, $\gamma(t)$ denotes the largest surplus-maximizing effort, and the Decentralization Penalty at t is again

$$D(t) = [\overline{R}^{\gamma(t)} - \overline{R}^{\delta(t)}] + t \cdot (C_{\delta(t)} - C_{\gamma(t)}).$$

We now have a lemma which is an analog of Lemma 1. It concerns the effect of a drop in t on the Principal-favorite effort and the surplus-maximizing effort when bonus contracts must be used.

Lemma 3

If bonus contracts must be used, then $t_L < t_H$ implies $\gamma(t_L) \geq \gamma(t_H)$. and $\delta(t_L) \geq \delta(t_H)$.

The easy proof of the claim about $\gamma(\cdot)$ is the same as in Lemma 1 and the proof of the claim about $\delta(\cdot)$ again uses strong duality.

4.2 The Behavior of the Decentralization Penalty when bonus contracts are used

We now turn to the behavior of the Decentralization Penalty for bonus contracts. We start with a lemma.

Lemma 4

If bonus contracts must be used, then $\delta(t) \leq \gamma(t)$ for all $t > 0$. (The Principal never squanders).

[16] As we shall see in section 6.1, it *can* happen when contracts are unrestricted.

This is important, as we noted after stating Lemma 2. If we indeed have no-squandering, then, when technology improves (t drops), the Penalty *rises* whenever it changes continuously. In the proof (which uses the inequalities in (2)), we establish a stronger statement. We compare the Principal's net gain when she optimally induces *any* surplus-maximizing effort, say the effort $\tilde{\gamma}(t)$, with her net gain when she optimally induces $f > \tilde{\gamma}(t)$. We show that the second of those net gains cannot be larger than the first. That implies $\delta(t) \leq \tilde{\gamma}(t)$.

If we now make the MLR and Approximate-concavity assumptions, then the following proposition fully characterizes the behavior of the Decentralization Penalty when bonus contracts are used.

Proposition 1.

Suppose the Monotone Likelihood Ratio property and the Approximate-concavity property hold. Suppose the Principal is required to use a bonus contract. Then the Penalty is zero for sufficiently small and sufficiently large t. Either the Penalty is zero at *all* t, or else there are intervals of finite length in each of which $D(t)$ begins with an upward jump to a positive number. After the jump, the Penalty decreases linearly until the end of the interval. So as production technology advances — as t *drops* — there are intervals where the Penalty linearly increases and there are points at which the Penalty suddenly drops. There are no intervals where the Penalty continuously falls as technology advances and there are no points at which it suddenly rises.

Formally: Either $D(t) = 0$ at all t, or else there exist numbers $t_1, \ldots, t_q, \ldots, t_Q$ such that $Q > 1$, $0 < t_1 < \cdots < t_Q$, and the following statements hold:

(i) $D(t) = 0$ for $t \leq t_1$ and for $t \geq t_Q$.

(ii) For every $q \in \{1, \ldots, Q-1\}$ and every $t \in (t_q, t_{q+1}]$, there exist G_q, u_q such that

$$D(t) = \frac{G_q - u_q}{t_{q+1} - t_q} \cdot (t_{q+1} - t) + u_q$$

and either $G_q = u_q = 0$ or $G_q > u_q \geq 0$. Moreover, $G_{q+1} \geq u_q$.

The proposition says that if t is sufficiently high then the lowest possible effort is both surplus-maximizing and Principal-favorite, so the Penalty is zero. As production technology improves (t falls), the Decentralization Penalty follows a continuous-rise-sudden-drop cycle until the production cost is low enough that the highest possible effort is both surplus-maximizing and Principal-favorite. Then the Penalty is again zero. We show in the proof that if, at some t, there is a sudden drop in the Penalty as technology improves, then it must be the case that for some q we have $t = t_{q+1}$ and $G_q > u_q$.

Intuitively, the Penalty is positive if and only if the Principal-favorite effort is strictly lower than the surplus-maximizing effort. That happens when the Principal's production-cost saving due to lower effort outweighs her loss of expected revenue. If the Principal-favorite effort is lower than the surplus-maximizing effort and both efforts *stay the same* throughout a t-interval, then throughout that interval the Penalty increases linearly as production technology improves (t drops): the cost saving due to the Principal's preference for an effort less than the surplus-maximizing effort (i.e., $t \cdot [C_{\gamma(t)} - C_{\delta(t)}]$) decreases (linearly), while the loss in expected revenue (i.e., $\overline{R}^{\gamma(t)} - \overline{R}^{\delta(t)}$) is unchanged. Once in a while, however, there will be a sudden production-technology breakthrough. Then the Principal-favorite effort jumps upward and moves closer to the surplus-maximizing effort. That means, as we shall show (using Approximate-concavity), that the Penalty suddenly drops, i.e., it jumps downward. So sudden breakthroughs always strengthen the social-welfare case for the Decentralized mode.

Formally, $D(\cdot)$ has a downward jump at t_{q+1} when technology improves (t drops) if

$$D(t_{q+1} + \epsilon) < D(t_{q+1}) \text{ for all sufficiently small positive } \epsilon.$$

Proposition 1 tells us that the only discontinuities in $D(\cdot)$ are such downward jumps. That means that $D(\cdot)$ is *left-continuous*.[17]

The proof shows, using Approximate-concavity, that as production technology improves (t drops), the only possible jump in the Penalty as technology improves is indeed a downward jump. Inspecting the proof, we will see that when Approximate-concavity is dropped (but MLR is retained) an upward jump as technology improves cannot be excluded. Then the "continuous-rise-sudden-drop" cycle can no longer be claimed. Instead we may claim a more complex "continuous-rise-sudden-*change*" cycle.

We illustrate the typical shape of $D(t)$ with the following example.

Example 1

There are three efforts and three revenues ($E = S = 3$). The revenue distributions for the three efforts are as follows:

	R_1	R_2	R_3
effort 1	$p_1^1 = \frac{3}{10}$	$p_2^1 = \frac{2}{10}$	$p_3^1 = \frac{5}{10}$
effort 2	$p_1^2 = \frac{2}{10}$	$p_2^2 = \frac{2}{10}$	$p_3^2 = \frac{6}{10}$
effort 3	$p_1^3 = \frac{1}{10}$	$p_2^3 = \frac{1}{10}$	$p_3^3 = \frac{8}{10}$

Let $(C_1, C_2, C_3) = (2, 3, 9)$ and let $(R_1, R_2, R_3) = (1, 3, 10)$.

Note that both MLR and IMCP are satisfied.[18] The Penalty is graphed in Figure 1.[19] For the Penalty behavior described by Proposition 1, Approximate-concavity is a sufficient condition

[17] One can also show that the left-continuity of $D(\cdot)$ follows directly from our ties-broken-upward assumption about the step functions $\gamma(\cdot)$ and $\delta(\cdot)$.

[18] We have $v_1 = C_1/p_3^1 = 4$, $v_2 = (C_2 - C_1)/(p_3^2 - p_3^1) = 10$, and $v_3 = (C_3 - C_2)/(p_3^3 - p_3^2) = 30$. So IMPC is satisfied

[19] The Decentralization Penalty is calculated for all t in $\left\{\frac{1}{100}, \frac{2}{100}, \cdots, \frac{99}{100}, 1\right\}$.

(together with MLR) , but not a necessary one. Nevertheless, it is useful to check whether we indeed have Approximate -concavity in this example. It turns out that we do.[20]

Finally, since IMCP is satisfied, the Principal loses nothing if she is required to use a bonus contract.[21] The Penalty is graphed in Figure 1.[22] The figure shows jumps, which — as Approximate-concavity implies — are *downward* when we go from right to left. We can interpret those jumps as technology breakthroughs, which strengthen the social-welfare case for Decentralization. The figure also has intervals where the Penalty changes continuously. The Penalty *rises* as technology improves in those intervals. Recall that this happens because, as Lemma 4 states, no-squandering holds for bonus contracts.

[FIGURE 1 HERE]

As we noted, Proposition 1 implies that the Penalty is left-continuous in t. We label the values of γ and δ in five intervals. When we move *from right to left*, these values do not decrease. We find two points of t where the Penalty suddenly drops to zero. Each drop is indicated by broken vertical lines. Each drop is preceded by an interval where the Principal does not squander and the Penalty linearly rises as t decreases. Thus, proceeding from right to left, Figure 1 illustrates the continuous-rise-sudden-drop cycle of the Decentralization Penalty for bonus contracts when we assume both MLR and Approximate-concavity. For specific values of the control cost K, we can identify production technologies where the Decentralized mode is welfare-superior and technologies where the Centralized mode is superior. For $t \in (.2, .9)$ and $t \in (.49, .6)$, the Decentralized mode is superior if $K > .9$ and the Centralized mode is superior if $K < .9$.

4.3 Bonus contracts when there are only two efforts.

As we have noted, Balmaceda *et al* show that if we make the IMCP assumption (as well as MLR), then the Principal loses nothing when she confines attention to bonus contracts. The

[20]Since there are only three efforts, there is only one possible violation of Approximate-concavity: for some t, say t^*, surplus *falls* when we go from effort 1 to effort 2. and then *rises* when we go from effort 2 to effort 3. We can rule out such a t^*. First consider the three surpluses. They are:

$$\overline{R}^1 - t^*C_1 = \frac{59}{10} - 2t^*,\ \overline{R}^2 - t^*C_2 = \frac{68}{10} - 3t^*,\ \overline{R}^3 - t^*C_3 = \frac{84}{10} - 9t^*.$$

If surplus falls when we go from effort 1 to effort 2, then $\frac{59}{10} - 2t^* > \frac{68}{10} - 3t^*$. That simplifies to

$$(+) \qquad t^* > \frac{9}{10}.$$

If surplus rises when we go from effort 2 to effort 3, then $\frac{84}{10} - 9t^* > \frac{68}{10} - 3t^*$, which simplifies to

$$(++) \qquad t^* < \frac{4}{15}.$$

But (++) contradicts (+). So Approximate-concavity is not violated.

[21]We have $v_1 = C_1/p_3^1 = 4$, $v_2 = (C_2 - C_1)/(p_3^2 - p_3^1) = 10$, and $v_3 = (C_3 - C_2)/(p_3^3 - p_3^2) = 30$. So IMCP is satisfied.

[22]The Decentralization Penalty is calculated for all t in $\left\{\frac{1}{100}, \frac{2}{100}, \cdots, \frac{99}{100}, 1\right\}$.

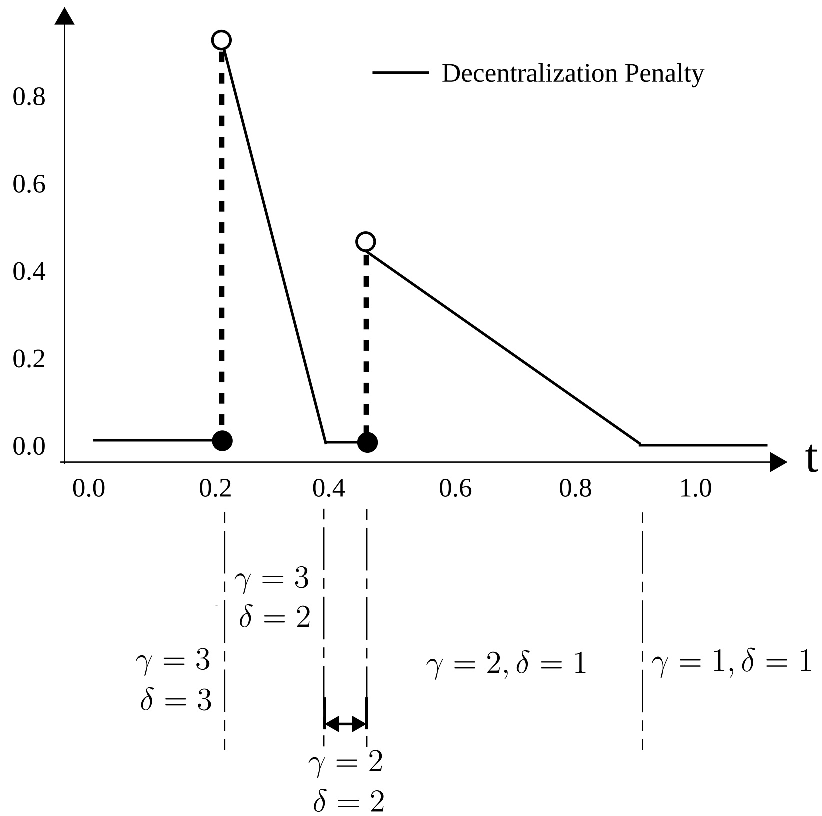

Figure 1 (Example 1)

IMCP requirement is strong (it involves both probabilities and costs). In the case of two efforts, however, we can show that IMCP is both necessary and sufficient for the Principal to lose nothing by confining attention to bonus contracts.

To be precise, we claim the following (for any fixed t):

(+) The triple $\big((C_1, C_2)\ ,\ \{R_s\}_{s=1,\ldots,S}\ ,\ (p^1, p^2)\big)$ has the IMCP property if and only if it has the following property for *each* of the two efforts:

(a) there is a bonus contract w which optimally induces the effort

(b) any non-bonus contract which induces the effort costs the Principal at least as much as w.

The argument has four parts.

(i): Effort e_1 can be bonus-induced if and only if IMCP holds.

If the bonus contract $(0, \ldots, 0, z)$ (with $z > 0$) induces e_1, then the following hold:

- The IR condition: $p^1_S z \geq tC_1$, i.e., $z \geq \frac{tC_1}{p^1_S}$.
- The IC condition $(p^1_S z - tC_1) \geq (p^2_S z - tC_2)$, i.e., $z \leq \frac{t\cdot(C_2 - C_1)}{p^2_S - p^1_S}$.

The two inequalities imply

$$\frac{C_1}{p^S} \leq \frac{C_2 - C_1}{p^2_S - p^1_S}.$$

That is the IMCP condition.[23] If IMCP is violated, the required z does not exist and e_1 cannot be optimally induced.

(ii): If IMCP holds there is a contract which optimally bonus-induces e_1.

Consider the bonus contract

$$w^* = \left(0, \ldots, 0, \frac{tC_1}{p^1_S}\right).$$

That contract bonus-induces e_1 and costs the Principal $p^1_S \cdot \dfrac{tC_1}{p^1_S} = tC_1$. Any non-bonus contract which also induces e_1 (whether it does so optimally or not) cannot cost the Principal less than tC_1. (Such a contract would violate the IR condition for inducement of e_1). So w^* optimally bonus-induces e_1.[24]

(iii): If IMCP holds there is a bonus contract which optimally bonus-induces e_2.

Consider the bonus contract

$$\tilde{w} = (0, 0, \ldots, 0, t\tilde{z}),$$

[23] Recall that IMCP says that $v_1 \leq v_2$, where $v_1 = \frac{C_1}{p^1_S}, v_2 = \frac{C_2 - C_1}{p^2_S - p^1_S}$.

[24] A non-bonus contract which optimally induces e_1 is $w = (tC_1, tC_1, \ldots, tC_1)$.

where

$$\tilde{z} = \frac{C_2 - C_1}{p_S^2 - p_S^1}.$$

The contract meets the IC condition for inducement of e_2 if and only if

$$tp_S^2\tilde{z} - tC_2 \geq tp_S^1\tilde{z} - tC_1.$$

or

$$\tilde{z} \geq \frac{C_2 - C_1}{p_S^2 - p_S^1}.$$

So the IC condition is met and binds. A cheaper bonus contract would not meet the IC condition.[25] Thus $\tilde{w}$ indeed optimally bonus-induces e_2.

(iv): If IMCP holds, an unrestricted contract which optimally induces e_2 cannot be cheaper than a bonus contract which optimally induces e_2.

We have to consider any contract — say $w' = (w'_1, \ldots, w'_S)$ — which also meets the induce-effort-2 IR and IC conditions, and we have to show that w' is not cheaper than $\tilde{w}$, i.e., $\overline{w'}^2 \geq \overline{\tilde{w}}^2$. To show this we use results from Balmaceda *et al.* They provide an argument that uses MLR as well as IMCP and shows that we can construct a new contract which also meets IR and IC, does not cost more than w', and has a component that equals zero. Applying this procedure to each of the first $S-1$ components, one at a time, we end up with a bonus contract whose cost to the Principal cannot be higher than $\overline{w'}^2$.[26]

That completes the proof of statement (+).

5. Fixed-share Contracts

We now turn to another type of simple contract. A contract w has the fixed-share property if

$$w = (rR_1, rR_2, \ldots, rR_S),$$

[25] The IR condition is $\tilde{z} \geq C_2$. Some manipulation shows that $C_2 > \frac{C_2 - C_1}{p_S^2 - p_S^1}$. So IR is satisfied.

[26] The argument is much simpler for the two-revenue case ($S = 2$). Any contract $w = (w_1, w_2)$ which induces x_2 satisfies the IC condition

$$w_1 \cdot (p_1^2 - p_1^1) + w_2 \cdot (p_2^2 - p_2^1) \geq t \cdot (C_2 - C_1),$$

which we can rewrite (using $p_1^1 = 1 - p_2^1, p_1^2 = 1 - p_2^2$) as

$$(\dagger) \qquad w_2 - w_1 \geq t \cdot \frac{C_2 - C_1}{p_2^2 - p_2^1}.$$

The bonus contract $\tilde{w} = (\tilde{w}_1, \tilde{w}_2) = \left(0, t \cdot \dfrac{C_2 - C_1}{p_S^2 - p_S^1}\right)$ satisfies the IC condition (†) as an identity. We have $\overline{\tilde{w}}^2 = p_2^2\tilde{w}_2$. If a different contract, say $w' = (w'_1, w'_2)$, also induces effort 2, then it must also satisfy (†). So we must have $w'_1 \geq 0, w'_2 \geq \tilde{w}_2$, and hence w' must cost at least as much as $\tilde{w}$, i.e., $\overline{w'}^2 = p_1^2 w'_1 + p_2^2 w'_2 \geq p_2^2\tilde{w}_2$. It follows that $\tilde{w}$ optimally induces effort 2, as claimed.

where $0 \leq r \leq 1$. At a given t, the Principal chooses r and the Agent responds by choosing the effort he finds best. The Principal chooses r so as to maximize her expected net gain.[27]

Given r, the Agent's net gain for an effort e is $r\overline{R}^e - tC_e$. Let $\hat{e}(r,t)$ denote the Agent's best response to r. It is the largest element of the set

$$\text{argmax}_{e\in\{1,\ldots,E\}} \left[r\overline{R}^e - tC_e\right].$$

The Principal keeps the fraction $1-r$ of expected revenue and the Agent receives the rest. If the Agent receives *all* of the expected revenue (i.e., $r=1$), then the effort he chooses maximizes welfare. Knowing the Agent's response to every r, the Principal chooses the share $r^*(t)$. That is the smallest element of the set

$$\text{argmax}\ _{r\in[0,1]}\ [(1-r)\cdot \overline{R}^{\hat{e}(r,t)}].$$

We shall confine attention to triples $(\{C_e\}_{e=1,\ldots,E}\ ,\ \{R_s\}_{s=1,\ldots,S}\ ,\ \{p^e\}_{e=1,\ldots,E})$ for which

- MLR holds, so $\overline{R}^e$ is again strictly increasing in e.
- $\hat{e}(r,t)$ exists for every pair (r,t) with $0 < r \leq 1, t \geq 0$.
- The share $r^*(t)$ exists for every $t \geq 0$.

With an abuse of notation, we now let $\delta(t)$ denote the *Principal-favorite effort at t under fixed-share contracts*. We have $\delta(t) = \hat{e}(r^*(t),t)$. The surplus-maximizing effort is $\gamma(t) = \hat{e}(1,t)$.

We now have a counterpart of Proposition 1 for fixed-share contracts.

Proposition 2

Suppose MLR and Approximate-concavity hold. Then the behavior of the Decentralization Penalty when fixed-share contracts are used is the same as the behavior (described in Proposition 1) when bonus contracts are used.

To prove Proposition 2 we show that the step functions $\gamma(\cdot)$ and $\delta(\cdot)$ again have the previous key properties: $\delta(\cdot)$ and $\gamma(\cdot)$ are weakly decreasing (Lemma 3); there is no squandering (Lemma 4); and $\delta(t) = \gamma(t)$ for sufficiently large and sufficiently small t. Examining the proof of Proposition 1, we see that those key properties, together with the MLR and Approximate-concavity conditions, are all that we need to derive the Proposition-1 properties of the Penalty. The techniques used to establish Lemma 3 and Lemma 4 for fixed-share contracts are very different than those we use for bonus contracts. In particular, we do not use linear-programming duality. Instead we use standard tools from monotone comparative statics. If we do not require

[27] Sharecropping is a form of fixed-share contract, widely used in agrarian economies. Laffont and Matoussi (1995) investigate, theoretically and empirically, whether increasing the share in such contracts raises surplus. In Marschak and Wei (2019), we study a similar problem for fixed-share contracts when there is no uncertainty but the set of efforts is allowed to be finite or infinite. Like a bonus contract, a fixed-share contract is linear in the revenues. The merits of linearity play a prominent role in the moral-hazard literature; see, e.g., Kim and Wang (1998), Bose *et al* (2011), Carroll (2015).

Approximate-concavity then the Penalty may behave differently: there may now be an upward jump when technology improves.

6. Variations

The previous analysis concerned the welfare loss due to decentralization when contracts are restricted to certain types. In this section we show by an example that some of our results may no longer hold when contracts are unrestricted. We also discuss an alternative criterion for judging the cost of decentralization, namely the loss in expected profit. We conclude with brief remarks about infinite effort sets.

6.1 Unrestricted Contracts

If we do not restrict the Principal's contracts, the Penalty's behavior may be different. In particular, squandering may occur and there may be intervals where the Penalty continuously rises and other intervals where it continuously falls. That is illustrated in the following example. A variation of the example shows, moreover, that it may cost the Principal more to induce a lower effort.

Example 2

There are three efforts and three revenues ($E = S = 3$). The revenue distributions for the three efforts are as follows:

	R_1	R_2	R_3
effort 1	$p_1^1 = \frac{5}{10}$	$p_2^1 = \frac{3}{10}$	$p_3^1 = \frac{2}{10}$
effort 2	$p_1^2 = \frac{4}{10}$	$p_2^2 = \frac{3}{10}$	$p_3^2 = \frac{3}{10}$
effort 3	$p_1^3 = \frac{1}{10}$	$p_2^3 = \frac{1}{10}$	$p_3^3 = \frac{8}{10}$

Let $(C_1, C_2, C_3) = (2, 4, 8)$ and let $(R_1, R_2, R_3) = (2, 3, 4)$.

Note that IMCP is violated.[28] If it were satisfied then (as we noted in Section 4) bonus contracts would optimally induce any given effort, and so the Penalty would have the Proposition-1 (and Figure-1) properties. The Penalty is graphed in Figure 2.[29] Note that MLR is satisfied. Approximate-concavity, however, is now violated.[30]

[FIGURE 2 HERE]

[28]We have $v_1 = C_1/p_3^1 = 10$, $v_2 = (C_2 - C_1)/(p_3^2 - p_3^1) = 20$, and $v_3 = (C_3 - C_2)/(p_3^3 - p_3^2) = 8$.

[29]As in Figure 1, the Penalty is calculated for all t in $\left\{\frac{1}{100}, \frac{2}{100}, \cdots, \frac{99}{100}, 1\right\}$. The graph is not drawn to scale, so that the narrow interval $[.58, .61]$ can be more easily visualized.

[30]There is only one possible violation of Approximate-concavity: for some t, say $\tilde{t}$, surplus *falls* when we go from effort 1 to effort 2 and rises when we go from effort 2 to effort 3. The three surpluses are:

$$\overline{R}^1 - \tilde{t}C_1 = \frac{27}{10} - 2\tilde{t},\ \overline{R}^2 - \tilde{t}C_2 = \frac{29}{10} - 4\tilde{t},\ \overline{R}^3 - 8\tilde{t} = \frac{37}{10} - 8\tilde{t}.$$

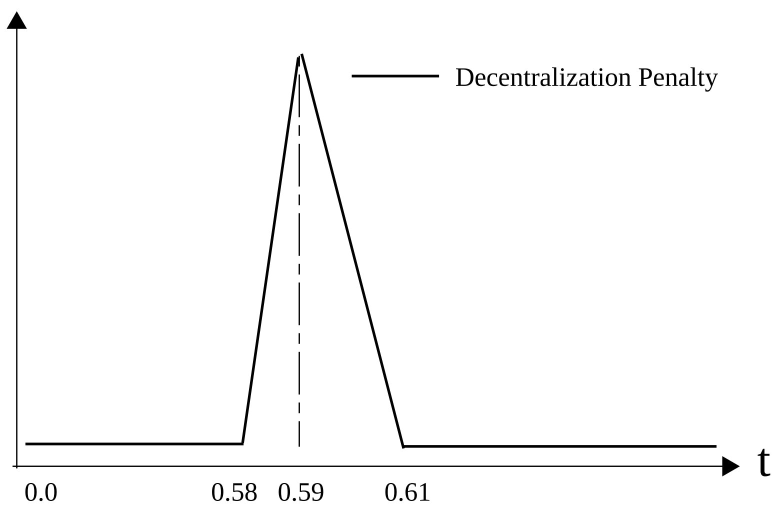

Figure 2 (Example 2)

We find that for $t < .58$ and $t \geq .61$ we have $\delta(t) = \gamma(t)$, so the Penalty is zero. For $.59 < t \leq .61$ we have $\delta(t) < \gamma(t)$. The Principal does not squander and the Penalty rises when t drops. But for $.58 < t \leq .59$ we have $\delta(t) > \gamma(t)$. The Principal squanders and the Penalty falls when t drops. A small variation of the example illustrates that when bonus contracts are not required, then it may cost *less* to induce a higher effort.[31]

6.2 An Alternative Criterion: Expected Profit

We now compare the Centralized and Decentralized modes in a new way. We judge them from the viewpoint of the firm's owner, who is concerned with expected profit, not welfare. The firm's expected revenue again depends on the effort the Agent chooses. In the Centralized mode, control techniques again enable the owner to enforce any effort she wants, and the Agent only needs to be compensated with the effort cost he incurs. Thus in the Centralized mode, the owner selects the effort $\gamma(t)$, a maximizer of expected surplus. In the Decentralized mode, there is no control. The owner of the firm becomes a Principal, who generally has to pay the Agent more than the cost of his effort. The Principal will induce her favorite effort $\delta(t)$, as given in Definition 3.

While the decreasing step functions $\gamma(\cdot)$ and $\delta(\cdot)$ are the same as in our welfare analysis, the new Decentralization Penalty differs from the previous one. The expected-profit Penalty is

$$(3) \qquad \tilde{D}(t) \equiv \left[\overline{R}^{\gamma(t)} - tC_{\gamma(t)}\right] - \left[\overline{R}^{\delta(t)} - A_{\delta(t)}(t)\right] = \overline{R}^{\gamma(t)} - \overline{R}^{\delta(t)} + (A_{\delta(t)}(t) - tC_{\gamma(t)}),$$

where $A_e(t)$ again denotes the lowest cost of inducing effort e.

How does $\tilde{D}$ behave? Note first that by equations (1) (at the end of Section 2) and (3), we have

$$\tilde{D}(t) - D(t) = A_{\delta(t)}(t) - tC_{\delta(t)} \geq 0,$$

which is nonnegative because of the IR requirement. So the welfare Penalty is bounded from above by the expected-profit Penalty. That implies that whenever the Decentralization mode is preferred by the firm's owner, it is also preferred from the welfare point of view.

If surplus falls when we go from effort 1 to effort 2, then $\frac{27}{10} - 2\tilde{t} > \frac{29}{10} - 4\tilde{t}$, which simplifies to

$$(\dagger) \qquad \tilde{t} > \frac{1}{10}.$$

If surplus rises when we go from effort 2 to effort 3, then $\frac{29}{10} - 4\tilde{t} < \frac{37}{10} - 8\tilde{t}$, which simplifies to

$$(\dagger\dagger) \qquad \tilde{t} < \frac{1}{5}.$$

There exists $\tilde{t}$ satisfying (†) and (††). So Approximate-concavity is violated.

[31] If we let $(C_1, C_2, C_3) = (2, 4, 10)$, then we find that e_2 is optimally induced by the contract $(0, 20, 20)$ which costs 12, but e_3 is optimally induced by the contract $(0, 0, 13.33)$ which costs 10.67. Note that if there are only two efforts, then it can never happen that the higher effort costs less. It is easily shown that it costs the Principal tC_1 to (optimally) induce effort 1. If effort 2 (the only other effort) is optimally induced by a wage vector $\tilde{w}$, then $\tilde{w}$ satisfies the IR requirement $\overline{\overline{w}}^2 \geq tC_2$, where $\overline{\overline{w}}^2$ is the cost of the higher effort. Since $C_2 > C_1$, it costs the Principal more to induce the higher effort.

But we cannot claim more. The no-squandering condition does not imply further statements about the shape of $\tilde{D}$.[32] Further assumptions on costs, revenues and probabilities are needed. That remains an interesting direction for future research.

6.3 Infinite effort sets.

This is a major variation, requiring a new research path that we shall not pursue here. Consider a simple example. The effort set is the entire interval $[0, 1]$ and there are just two revenues, namely $R_1 = 0$ and $R_2 = 1$.[33] The probability of R_2 given the effort e is just e itself. Hence (since $R_1 = 0$) expected revenue is also e itself. The cost of effort e is $tC(e)$. Thus surplus at e is $e - tC(e)$ and the function $C(\cdot)$ defines the problem. We require $C(0) = 0, C' > 0, C'' > 0$, so surplus is strictly concave in e. The Principal induces an effort by choosing a bonus contract w which pays the Agent w if and only if revenue turns out to be one. The Agent responds to w by choosing an effort which maximizes $we - tC(e)$. The Principal's optimally-induce-e problem is now a semi-infinite linear programming problem, since w has to satisfy a continuum of IC constraints, one for each effort in $[0, 1]$. But under our assumptions all except a finite subset of the constraints are not binding. Hence the semi-infinite problem can be replaced by a standard finite linear programming problem where strong duality holds.[34] We can then use strong duality to prove an analog of Lemma 3 ($\gamma(\cdot)$ and $\delta(\cdot)$ are nonincreasing).

It is also straightforward to show that we have an analog of Lemma 4: we again have No-squandering ($\delta(\cdot) \le \gamma(\cdot)$). But now the only t-interval where the Principal-favorite effort and the surplus-maximizing effort are constant is the initial interval where t is so small that both efforts equal the largest effort (which is one). So No-squandering no longer implies that in any t-interval where the Penalty continuously changes, it must be decreasing in t.[35] In the case $C(e) = e^a, a > 1$, we have an interval where the Penalty continuously rises, followed by another interval where it continuously drops. The Penalty is single-peaked. Its graph resembles Figure 2, but the rising and falling lines now have curvature instead of being straight. Details are provided in Marschak (2022).

7. Economic examples.

Can we find classic conditions on costs and revenues which imply that the Penalty behaves in a certain way? In a previous paper[36] — where there is no uncertainty and the set of efforts is allowed to be finite or infinite, a continuum — results of that kind turned out to be scarce. But

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[32] The behavior of $\tilde{D}$ depends on the sign of $A_{\delta(t)}(t) - tC_{\gamma(t)}$. Even if $\delta(t) \le \gamma(t)$ for all t (so that $tC_{\gamma(t)} \ge tC_{\delta(t)}$), the comparison between $A_{\delta(t)}(t)$ and $tC_{\gamma(t)}$ is still ambiguous because IR implies that $A_{\delta(t)}(t) \ge tC_{\delta(t)}$.

[33] Models with those properties are studied in Laffont and Martimort (2002) and Salanié (2005).

[34] The argument for that assertion can be found in Nasri *et al* (2015) and Nasri (2015). It uses basic propositions in semi-infinite programming. Those are found in surveys of the extensive literature by, for example, Hettich and Kortanek (1993) and Shapiro (2005).

[35] Recall that we obtain that result in our finite-effort model because there may be intervals where t is neither very small nor very large but the Principal-favorite and welfare-maximizing efforts remain constant as t changes. On such an interval the term $\overline{R}^{\gamma(t)} - \overline{R}^{\delta(t)}$ is constant and the behavior of the Penalty is determined by the term $-t \cdot (C_{\gamma(t)} - C_{\delta(t)})$, which (because of No-squandering) is negative when $\gamma(t) \ne \delta(t)$.

[36] Marschak and Wei (2019).

there was one such result. To obtain it, we assumed that the effort set is an interval and the firm is a price-taker: each effort is a product quantity and the product sells at a price which the firm takes as given. So marginal revenue is flat. We also assumed that marginal cost increases linearly. We let the Principal use a fixed-share contract, where the share is the Principal's favorite. We then found that at every t the Penalty is decreasing in t: a technical improvement (a drop in t) smoothly raises the Penalty. In the present paper's model there are S revenues and E efforts.

The "flat marginal revenue" condition is:

$$\text{there exists } H \text{ such that } R_s - R_{s-1} = H \text{ for all } s \text{ in } \{2, \ldots, S\}.$$

The "increasing marginal cost" condition is:

$$C_2 - C_1 < C_3 - C_2 < \cdots < C_{E-1} - C_{E-2} < C_E - C_{E-1}.$$

If bonus or fixed share contracts are used, then *whether or not* marginal revenue is flat and marginal cost is increasing, we have the Penalty behavior of Proposition 1. So if there is an interval where the Penalty smoothly changes when t drops, then it must be an interval where the Penalty increases when t drops. That is also true in the price-taking-firm result of our previous paper.

But our moral-hazard model of the Decentralized mode has a weakness: the probabilities are not explained. Can we obtain results about the Penalty if costs and revenues obey classic conditions and the probabilities are *endogenously* determined from the nature of the firm's effort-choosing task? Do those probabilities obey the MLR condition?

Consider the following example.

The firm has E potential buyers of its product. A true buyer buys one unit, but only after personal contact with the firm. The true buyer pays the firm a price that equals one plus the cost of producing one unit. So the revenue collected by the firm equals the number of contacted buyers who turn out to be true buyers. Advertising effort, chosen by an Agent, increases the number of potential buyers who would turn out to be true buyers if they were contacted. The Agent's effort is induced by a Principal, who (as before) induces her favorite effort

The possible advertising efforts are $1, \ldots, e, \ldots E$. If the effort e is spent on advertising, then e of the E potential buyers become true buyers when contacted. Effort e costs tC_e, where C_e is strictly increasing in e. $S \leq E$ potential buyers are randomly chosen and contacted. If s of the S contacted buyers turn out to be true buyers then the firm collects the revenue R_s. So the possible revenues are $\{R_1, \ldots, R_s, \ldots, R_S\} = \{1, 2, \ldots, s, \ldots, S\}$. (So the "flat marginal revenue" condition is satisfied). The S randomly chosen potential buyers are a sample without replacement. For a given effort e, the probability that the sample contains s true buyers (so revenue is R_s) is given by the hypergeometric distribution. So

$$p_s^e = \frac{\binom{e}{s} \cdot \binom{E-e}{S-s}}{\binom{E}{S}},$$

and, in particular,

$$p_S^e = \frac{\binom{e}{S}}{\binom{E}{S}}.$$

The hypergeometric distribution has the MLR property.[37] Hence so does our family of probabilities $\{p_s^e\}_{e=1,\ldots,E;s=1,\ldots,S}$. If we now *require* the firm to use bonus (or fixed-share) contracts, then we get the Proposition-1 behavior of the Penalty.[38]

Finding other examples where endogenous probabilities and classic economic conditions restrict the behavior of the Penalty is a challenge that merits further attention.[39]

8. Concluding Remarks.

The dramatic and rapid advances that we observe in production technology and in control technology strongly motivate a better understanding of the effect of advances in production technology on the merits of the Decentralized and Centralized modes. But it is difficult to formulate the question with sufficient precision so that answers can be found. Clearly we have to start with highly simplified models. To model the Decentralized mode it is natural to try the standard moral-hazard Principal/Agent framework.

While an improvement in control technology always strengthens the social-welfare case for the Decentralized mode, advances in production technology may do the opposite. We saw this in the sharp statements we established about the behavior of the Decentralization Penalty in response to improvements in production technology. We found that when the Principal is restricted to use either bonus contracts or fixed-share contracts, the Decentralization Penalty will oscillate in a continuous-rise-sudden-change cycle until production technology becomes sufficiently advanced. If we require expected revenues and costs to obey the Approximate-concavity condition, then the sudden changes are sudden drops. For a given control technology, breakthroughs in production technology strengthen the social-welfare case for the Decentralized mode. On the other hand, there are no intervals where technology improvement smoothly lowers the Penalty. These results use the fact that under both contract types the Principal never squanders.

There are many ways to vary and extend our finite-effort model. Here are a few of them.

[37] That means that the fraction

$$\frac{\text{probability that the sample has } i \text{ true buyers when effort is } e}{\text{probability that the sample has } j \text{ true buyers when effort is } e}$$

is increasing in e if $i > j$. For a proof that the hypergeometric distribution has the MLR property see Lehman (1986), p.80.

[38] If the IMCP condition were satisfied, then the firm loses nothing if it uses bonus contracts, and we get the Penalty behavior of Proposition 1 without requiring the firm to use bonus contracts. Unfortunately, however, we can easily find $C_1, \ldots, C_E$ so that the IMCP condition is violated even though marginal cost is increasing and marginal revenue is flat. Let $E = 20, S = 10$. Then we find — rounding to five decimal places — that $p_S^1 = .00036, p_S^2 = .00542$. Now let $C_e = e^2$ for all e in $\{1, \ldots, E\}$, so the increasing-marginal-cost condition is satisfied. Thus $C_1 = 1, C_2 = 4$. IMCP requires that $v_1 \leq v_2$, where $v_1 = C_1/p_S^1, v_2 = (C_2 - C_1)/(p_S^2 - p_S^1)$. That is equivalent to $C_1 p_S^2 \leq C_2 p_S^1$ or $p_S^2 \leq 4p_S^1$. That is violated, since $.00542 > (4) \cdot (.00036) = .00144$.

[39] Economic examples where IMCP holds endogenously would be of particular interest. Note that if marginal cost is flat or rising, then we have IMCP if $p_S^e - p_S^{e-1}$ is decreasing in e.

- Find other contract types where the Principal never squanders and study the Penalty for each type.

- Make the Agent risk-averse. In the simplest model, the Agent chooses the effort e if $\overline{w^*} \geq tC_e$ and $\overline{w^*} - tC_e \geq \overline{w^*} - tC_f$ for all f, where $w^* = (u(w_1), \ldots, u(w_S))$ and u is a strictly concave function. There may be functions u for which the behavior of the Penalty can be sharply characterized.

- Let t be a random variable whose average drops when technology improves. Let t be observed by only one of the two parties.

- Let there be several Agents. In the easiest case there are two Agents and the parameter t is known to all three parties. Realized revenue depends on the two Agents' efforts, and the probability of a given revenue for a given effort pair is common knowledge. The Principal uses a fixed-share contract or a bonus contract. She chooses two shares whose sum must lie between zero and one, or two bonus payments. Then in the Decentralized mode we have a three-player game for every t. Each Agent chooses an effort and the Principal chooses the two shares or the two bonus payments. Suppose that for every t the game has a unique pure-strategy equilibrium. To compute the Decentralization Penalty we first find the effort pair that maximizes surplus. We compare that surplus with surplus at the equilibrium. When t drops, does the Penalty rise or fall?

These variations, and many others, deserve attention.

APPENDIX

Proof of Lemma 1

It suffices to show that an effort which maximizes the Principal's net gain at t_H cannot be less then an effort which maximizes it at $t_L < t_H$. That is implied by the following stronger statement, which we now prove:

(A1) If $e > f$ and $\overline{R}^e - A_e(t_H) \geq \overline{R}^f - A_f(t_H)$ then for $t_L < t_H$ we have $\overline{R}^e - A_e(t_L) \geq \overline{R}^f - A_f(t_L)$

At every t, the Principal's (primal) optimally-induce-e problem is the following.

Find a wage vector $w = (w_1, \ldots, w_S)$ which minimizes $\sum_{s=1}^{S} p_s^e w_s$
subject to:

$w_s \geq 0, s = 1, \ldots, S$
$\sum_{s=1}^{S} p_s^e w_s \geq tC_e$ (IR)
$\sum_{s=1}^{S} (p_1^e - p_1^j) \cdot w_s \geq t \cdot (C_e - C_j), j = 1, \ldots, E.$ (IC)

If w solves the problem, then $A_e(t) = \sum_{s=1}^{S} p_s^e w_s$.

Recall that we confine attention to situations where the primal problem has a solution at every t. We now state the dual of the preceding problem. We let h denote the dual variable ("shadow price") associated with the IR constraint and we let $y_1, y_2, \ldots, y_E$ denote the dual variables associated with the E IC constraints. Then the dual is:

Find nonnegative shadow prices $h, y_1, \ldots, y_E$ which maximize

$$t \cdot [hC_e + \sum_{j=1}^{E} C_e - C_j]$$

subject to:

$$h + y_j \cdot (p_s^e - p_s^j) \leq p_s^e, s = 1, \ldots, S.$$

Strong duality tells us: (1) since the primal has a solution, say $w = (w_1, \ldots, w_S)$, the dual also has a solution, say $(h, y_1, \ldots, y_E)$; (2) the value of the minimand in a solution to the primal equals the value of the maximand in a solution of the dual. That means that inducing e costs the Principal

$$A_e(t) = \overline{w}^e = tJ_e,$$

where

$$J_e = hC_e + \sum_{j=1}^{E} y_j \cdot (C_e - C_j).$$

We have $J_e > 0$, since (by the IR requirement) $A_e(t) \geq tC_e > 0$. Consider $f > e$ and the optimally-induce-f problem. (By assumption, that problem has a solution at every t). The Principal (weakly) prefers f to e at t if

$$\overline{R}^f - \overline{R}^e \geq t \cdot (J_f - J_e) \qquad (A2)$$

(since $A_e(t) = tJ_e, A_f(t) = tJ_f$). Suppose $J_f \geq J_e$ and apply (A2) to the case $t = t_H$ and the case $t = t_L < t_H$. We see that if the Principal (weakly) prefers f to e at $t = t_H$, then she continues to do so at $t = t_L < t_H$. Suppose, on the other hand, that $J_f < J_e$ and apply (A2) again. The left side is positive; that follows from the MLR assumption. The right side is negative. So (A2) holds for $t = t_H$ and for $t = t_L$.

Thus the Principal cannot switch from weakly preferring f at $t = t_H$ to strongly preferring e at $t = t_L$. That establishes (A1) and Lemma 1. □

Proof of Lemma 3

The proof is analogous to the proof of Lemma 1. It suffices to show that an effort which maximizes the Principal's net gain at t_H, when she uses bonus contracts, cannot be less then an effort which maximizes it at $t_L < t_H$. That is implied by the following stronger statement, which we now prove:

(A3) If $e > f$ and $\overline{R}^e - A^b_e(t_H) \geq \overline{R}^f - A^b_f(t_H)$, then for $t_L < t_H$ we have $\overline{R}^e - A^b_e(t_L) \geq \overline{R}^f - A^b_f(t_L)$.

The Principal's (primal) optimally-bonus-induce-e problem is:

Find a nonnegative z which minimizes $p^e_S z$ subject to:

$$z \geq tC_e$$

$$z \cdot (p^e_S - p^j_S) \geq t \cdot (C_e - C_j), j = 1, \ldots, E.$$

The dual of this minimization problem is:

Find nonnegative shadow prices $h, y_1, \ldots, y_E$ which maximize

$$t \cdot [hC_e + \sum_{j=1}^{E} y_j \cdot (C_e - C_j)]$$

subject to

$$hC_e + \sum_{j=1}^{E} y_j \cdot (p^e_S - p^j_S) \leq p^e_S.$$

We confine attention to situations where the primal problem has a solution, say $z^e(t)$, which costs the Principal $A^b_e(t) = p^e_S z^e(t)$. Since $C_e > 0$ and $z_e(t)$ satisfies the IR condition $z_e(t) \geq tC_e$, where $C_e > 0$, we have $z_e(t) > 0$ and $A^b_e(t) > 0$. By strong duality: (1) the dual also has a solution, say $(h, y_1, \ldots, y_E)$, and (2) the value of the minimand in the solution to the primal equals the value of the maximand in the solution to the dual. That means

$$A^b_e(t) = t\tilde{J}_e, \text{ where } \tilde{J}_e = hC_e + \sum_{j=1}^{E} y_j \cdot (p^e_S - p^j_S \text{ and } \tilde{J}_e > 0.$$

That holds as well when we replace "e" with "f". We now verify (A3) by repeating the argument used to verify (A2) in the proof of Lemma 1, with $\tilde{J}_e, \tilde{J}_f$ replacing J_e, J_f. That completes the proof. □

Proof of Lemma 4

We first show, for a fixed t, that if $f > e$, then the Agent weakly prefers the optimal inducement of f to the optimal inducement of e, i.e.,

$$(A4) \qquad [A^b_f(t) - tC_f] - [A^b_e(t) - tC_e] \geq 0, \text{ if } f > e.$$

That is the case because, for any e, f such that $f > e$, we have:

$$(A5) \qquad A^b_f(t) - tC_f = p^f_S \cdot z^f(t) - tC_f \geq p^e_S \cdot z^f(t) - tC_e \geq p^e_S \cdot z^e(t) - tC_e = A^b_e(t) - tC_e.$$

The first inequality in (A5) follows from the "f-not-worse-than-e" IC condition for the inducement of effort f. The second inequality follows from $z^f(t) \geq z^e(t)$ (statement (2) in Section 4.1).

Next we consider *any* surplus-maximizing effort, say $\tilde{\gamma}(t)$, and we show that an effort greater than $\tilde{\gamma}(t)$ cannot be Principal-favorite, so we indeed have $\delta(t) \leq \tilde{\gamma}(t)$. To see this, for a fixed t, pick any effort $f > \tilde{\gamma}(t)$. Then

$$(A6) \qquad \left[\overline{R}^{\tilde{\gamma}(t)} - A^b_{\tilde{\gamma}(t)}(t)\right] - \left[\overline{R}^f - A^b_f(t)\right] = \underbrace{\left[\overline{R}^{\tilde{\gamma}(t)} - tC_{\tilde{\gamma}(t)}\right] - \left[\overline{R}^f - tC_f\right]}_{D_1 \geq 0}$$

$$+ \underbrace{\left[A^b_f(t) - tC_f\right] - \left[A^b_{\tilde{\gamma}(t)}(t) - tC_{\tilde{\gamma}(t)}\right]}_{D_2 \geq 0} \geq 0.$$

Here $D_1 \geq 0$ because the effort $\tilde{\gamma}(t)$ maximizes surplus, while $D_2 \geq 0$ follows directly from (A4). $\square$

Proof of Proposition 1.

Step 1: The Penalty $D(t)$ is zero for small t and large t.

Recall that

$$D(t) = [\overline{R}^{\gamma(t)} - \overline{R}^{\delta(t)}] + t \cdot \left(C_{\delta(t)} - C_{\gamma(t)}\right).$$

First we show that there exists $\bar{T} > 0$ such that $\gamma(t) = \delta(t) = 1$ for all $t > \bar{T}$. We have $\gamma(t) = 1$ (at t, the effort 1 maximizes surplus) if

$$\overline{R}^e - \overline{R}^1 \leq t \cdot (C_e - C_1) \text{ for all } e > 1.$$

By MLR we know that $\overline{R}^e - \overline{R}^1 > 0$ for all $e > 1$. Since $C_e > C_1$ for all $e > 1$, there exists $T_1 > 0$ such that

$$\overline{R}^e - \overline{R}^1 < t \cdot (C_e - C_1), \text{ for all } e > 1, t > T_1.$$

So $\gamma(t) = 1$ for all $t > T_1$.

We now turn to the Principal-favorite effort $\delta(t)$. We saw in the proof of Lemma 3 that $A^b_e(t) = \tilde{J}_e t$ for some $\tilde{J}_e \geq C_e$. So the Principal's net gain if she optimally induces e is $\overline{R}^e - t\tilde{J}_e$. Moreover, it is easy to verify that effort 1 can be optimally bonus-induced by the wage vector $(0, \ldots, z_1(t)) = (0, ..., 0, tC_1/p^1_S)$. Since $A^b_1(t) = p^1_S(t)$, we have $\tilde{J}_1 = C_1 < C_e \leq \tilde{J}_e$, for all $e > 1$. Therefore there exists $T_2 > 0$ such that the Principal maximizes her net gain by optimally inducing the effort 1, i.e.,

$$\overline{R}^e - \overline{R}^1 < t \cdot (\tilde{J}_e - \tilde{J}_1), \text{ for all } e > 1, t > T_2.$$

So $\delta(t) = 1$ for all $t > \bar{T}_2$. Letting $\bar{T} = \max\{T_1, T_2\}$, we conclude that $\gamma(t) = \delta(t) = 1$ for all $t > \bar{T}$.

Next we show that there exists $\bar{t} > 0$ such that $\gamma(t) = \delta(t) = E$ for all $t \in (0, \bar{t})$. Since $\overline{R}^E - \overline{R}^e > 0$ for all $e < E$, there exists t_1 such that

$$\overline{R}^E - \overline{R}^e > t \cdot (C_E - C_e), \text{ for all } e < E, t < t_1.$$

So $\gamma(t) = E$ for all $t \in (0, t_1)$. Moreover, there exists $t_2 > 0$ such that

$$\overline{R}^E - \overline{R}^e > t \cdot (\tilde{J}_E - \tilde{J}_e), \text{ for all } e < E, t < t_2.$$

So[40] $\delta(t) = E$ for all $t \in (0, t_2)$. Letting $\bar{t} = \min(t_1, t_2)$, we conclude that $\gamma(t) = \delta(t) = E$ for all $t \in (0, \bar{t})$.

We cannot have $\bar{T} < \bar{t}$.[41] If $\bar{T} = \bar{t}$, then $D(t) = 0$ at all $t > 0$.

We now turn to the case where there are intermediate values of t, i.e., $\bar{T} > \bar{t}$.

Step 2: Whenever $D(\cdot)$ jumps, the jump must be upward.[42]

To establish statement (ii) in the Proposition, we have to show that if there is a jump in the Penalty D at a t which lies in the interval $(t_q, t_{q+1}]$, then that jump must be upward. Informally, the argument is the following. The Penalty at t equals maximal surplus at t minus Decentralized surplus at t. Maximal surplus is (by the maximum theorem) continuous in t. So if the Penalty jumps at t, then there must be a jump in Decentralized surplus at t. Approximate Concavity implies that Decentralized surplus is a nonincreasing step function of t, and so it can only jump downward. That means the Penalty can only jump upward.

We now provide a formal version of the argument. We want to show that:

(A7) if D is discontinuous at t, then for all sufficiently small positive ϵ, we have $D(t + \epsilon) > D(t)$.

We prove it by contradiction. If (A7) were false, there would be a downward jump in the Penalty at some t. We would have:

(A8) At some $t > 0$, D is discontinuous and for all sufficiently small positive ϵ, we have $D(t + \epsilon) < D(t)$.

[40] In the proof of Lemma 3, we used (A2) in the proof of Lemma 1, which says (when adapted to the case of bonus contracts) that for $f > e$ we have $\overline{R}^f - \overline{R}^e \geq t \cdot (\tilde{J}_f - \tilde{J}_e)$, whether the term on the right of that inequality is positive, zero, or negative. But here "f" becomes E and we need not be concerned with the case where the term on the right is negative, since the IC condition for inducement of E requires that for $E > e$, we have $\tilde{J}_E - \tilde{J}_e \geq t \cdot (C_E - C_e) > 0$.

[41] We have (1) $\gamma(t) = \delta(t) = 1$ for all $t > \bar{T}$; and (2) $\gamma(t) = \delta(t) = E$ for all $t \in (0, \bar{t})$. If we had $\bar{T} < \bar{t}$, then there would exist $\hat{t} \in (\bar{T}, \bar{t})$ such that we have both $\gamma(\hat{t}) = \delta(\hat{t}) = 1$ and $\gamma(\hat{t}) = \delta(\hat{t}) = E$, which is a contradiction since $E > 1$.

[42] In interpreting "upward", remember that throughout this proof we are considering the "left-to-right" behavior of the Penalty (when t rises, production technology deteriorates).

To get our contradiction, we first claim the following general statement. It concerns Decentralized surplus, i.e., $\overline{R}^{\delta(t)} - tC_{\delta(t)}$. We claim that Decentralized surplus is (weakly) decreasing in t, i.e.,

$$(A9) \qquad \text{for } \epsilon > 0, \text{ and the efforts } \delta(t), \delta(t+\epsilon), \text{ we have: } \overline{R}^{\delta(t)} - tC_{\delta(t)} \geq \overline{R}^{\delta(t+\epsilon)} - tC_{\delta(t+\epsilon)}.$$

To see this, note first that Approximate-concavity tells us that the graph of the surplus $\overline{R}^{e} - tC_e$ (with e on the horizontal axis) rises until the effort $e^{\#}(t)$ is reached, where $e^{\#}(t)$ denotes the smallest maximizer of that surplus. Following $e^{\#}(t)$, the graph may be flat for a while and may then descend. Similarly, the graph of the surplus $\overline{R}^{e} - (t+\epsilon) \cdot C_e$ rises until the effort $e^{\#}(t+\epsilon)$ is reached, where $e^{\#}(t+\epsilon)$ denotes the smallest maximizer of that surplus; following $e^{\#}(t+\epsilon)$, the graph may be flat for a while and may then descend.

Next, note that by Lemma 1 and Lemma 4 (no-squandering), the following holds for the efforts $\delta(t+\epsilon), \delta(t)$, and the surplus $\overline{R}^{e} - tC_e$:

$$(A10) \qquad \delta(t+\epsilon) \leq \delta(t) \leq e^{\#}(t).$$

Recall that Approximate-concavity tells us that surplus drops whenever effort moves further below the smallest surplus-maximizer. Since $e^{\#}(t)$ is the smallest maximizer of the surplus $\overline{R}^{e} - tC_e$, Approximate-concavity tells us, using (A10), that

$$\text{if } \delta(t+\epsilon) < \delta(t) \text{ then } \overline{R}^{\delta(t+\epsilon)} - tC_{\delta(t+\epsilon)} < \overline{R}^{\delta(t)} - tC_{\delta(t)}.$$

On the other hand, if $\delta(t+\epsilon) = \delta(t)$ then the second of those two inequalities becomes an equality. So we have established (A9).

Next we minimize needless notational clutter by introducing two new symbols:

$$F(t) \equiv \overline{R}^{\gamma(t)} - tC_{\gamma(t)}; \ G(t) \equiv \overline{R}^{\delta(t)} - tC_{\delta(t)}.$$

So $F(t)$ is maximal surplus, $G(t)$ is Decentralized surplus, and the Penalty is $D(t) = F(t) - G(t)$. The maximum theorem tells us that F is continuous.

Using our new notation, the inequality $D(t+\epsilon) < D(t)$ in (A8) can be rewritten

$$F(t) - G(t) > F(t+\epsilon) - G(t+\epsilon),$$

or, rearranging:

$$F(t) - F(t+\epsilon) > G(t) - G(t+\epsilon).$$

Statement (A8) implies the following:

(A11) At some $t > 0$, $F - G$ is discontinuous and there exists a positive e^* such that for $0 < \epsilon \leq \epsilon^*$ we have

$$F(t) - F(t+\epsilon) > G(t) - G(t+\epsilon).$$

But since F is continuous, $F - G$ could not have the discontinuity asserted in (A11) if G remains constant as we vary ϵ, i.e., if $G(t) = G(t+\epsilon)$ for $0 < \epsilon \leq \epsilon^*$. Statement (A9), however, tells us that G is (weakly) decreasing. So if G is not constant, and if (A11) indeed holds, then the term $G(t) - G(t+\epsilon)$ must be *positive* at all $\epsilon \in (0, \epsilon^*]$; it cannot be less than some positive $L > 0$, no matter how small ϵ may be. Thus (A11) contains a contradiction, since the right side of the final inequality is at least $L > 0$ at all $\epsilon \in (0, \epsilon^*]$ but (by continuity of F) the left side can be made as small as we wish by taking ϵ sufficiently small. The "ϵ^*" described in (A11) cannot exist.

So (A11) and (A8) cannot hold and (A7) is correct. Whenever D jumps, the jump must indeed be upward.

Step 3: Defining G_q, u_q and verifying that they have the claimed properties.

We now define the terms G_q, u_q and show that for those definitions the statements in the Proposition hold. To do so, we use the results established in the previous steps.

Let G_q denote $\sup\{D(t) \ : \ t \in (t_q, t_{q+1})\}$ and let u_q denote $D(t_{q+1})$.

If $G_q > u_q$ then we have the *upward* jump in $D(\cdot)$ just after t_{q+1}, which, as Step 2 showed, is the only possible jump. We have: $D(t_{q+1} + \epsilon) < D(t_{q+1})$ for all sufficiently small positive ϵ. To see this, note first that

$$D(t_{q+1}) = \frac{G_q - u_q}{t_{q+1} - t_q} \cdot (t_{q+1} - t_{q+1}) + u_q = u_q,$$

so the equality (ii) in the statement of the Proposition is satisfied. Moreover,

$$D(t_{q+1} + \epsilon) = \frac{G_q - u_q}{t_{q+1} - t_q} \cdot (t_{q+1} - (t_{q+1} + \epsilon)) + u_q = \frac{G_q - u_q}{t_{q+1} - t_q} \cdot (-\epsilon) + u_q < u_q,$$

i.e., we would have an upward jump in $D(\cdot)$ just after t_{q+1}.

We also have $G_{q+1} \geq u_q$, as the Proposition asserts. If we had $u_q > G_{q+1}$, then throughout the interval $(t_q, t_{q+1}]$, the graph of D (with t on the horizontal axis) would be an *upward-sloping* straight line with slope $\dfrac{u_q - G_{q+1}}{t_{q+1} - t_q}$. To see that this is ruled out, recall that any interval in which the step functions $\gamma(\cdot), \delta(\cdot)$ are not equal has a subinterval where they are constant. So, in particular, the interval $(t_q, t_{q+1}]$ has a subinterval where $D(t) = \overline{R}^{\gamma'} - \overline{R}^{\delta'} + t \cdot (C_{\delta'} - C_{\gamma'})$ for some γ', δ'. Since (by Lemma 4) $\delta' \leq \gamma'$, D cannot slope upward on the subinterval and hence it cannot slope upward throughout the entire interval $(t_q, t_{q+1}]$.

That concludes the proof. $\square$

We noted in the text that if we drop the Approximate-concavity assumption (but we retain MLR) then we cannot exclude the possibility that when production technology improves (t

drops), there is a *downward* jump at some t. A downward jump — satisfaction of (A8) — cannot be ruled out.[43]

Proof of Proposition 2

We first establish fixed-share versions of Lemmas 3 and 4.

Step 1: proving that $t_L \leq t_H$ implies $\delta(t_L) \geq \delta(t_H)$ and $\gamma(t_L) \geq \gamma(t_H)$.

We use a standard proposition from monotone comparative statics. (See, for example, Sundaram (1996), Chapter 10).

Consider sets $U \in I\!R, V \in I\!R$ and a function $h : U \times V \to I\!R$. The two arguments of h are denoted u, v. The function h displays *strictly increasing differences in the variables* u, v if

$$h(u_H, v_H) - h(u_L, v_H) > h(u_H, v_L) - h(u_L, v_L)$$

whenever $u_H, u_L \in U$, $v_H, v_L \in V$, $u_H > u_L$, and $v_H > v_L$. We use the following proposition:

(#) Suppose that for every $v \in V$, the problem

$$\text{maximize } h(u, v) \text{ subject to } u \in U$$

has at least one solution. Suppose also that h satisfies strictly increasing differences in u, v. Consider $v_H, v_L \in V$ with $v_H > v_L$. Let u_H be a maximizer of $h(u, v_H)$ on U and let u_L be a maximizer of $h(u, v_L)$ on U. Then $u_H \geq u_L$.

Note the following:

(α) If h takes the form $h(u, v) = f(u, v) + g(u)$, then h displays strictly increasing differences in u, v if and only if f displays strictly increasing differences in u, v.

(β) If h takes the form $h(u, v) = f(u) \cdot g(v)$ and f and g are strictly increasing, then h displays strictly increasing differences in u, v.

Recall that $\delta(t) = \hat{e}(r^*(t), t)$. We first show that $\delta(t_L) \leq \delta(t_H)$ if $t_L < t_h$, i.e.,

$$(A12) \qquad \hat{e}(r^*(t_L), t_L) \geq \hat{e}(r^*(t_H), t_H) \text{ whenever } 0 < t_L < t_H.$$

We note first that the Agent's chosen effort $\hat{e}(r, t)$ depends only on the ratio $\frac{r}{t}$, which we shall call ρ. The set of possible values of ρ is $\left(0, \frac{1}{t}\right]$. The Agent's effort is a value of e which maximizes $r\overline{R}^e - tC_e = t \cdot (\rho\overline{R}^e - C_e)$ and is therefor a maximizer of $\rho\overline{R}^e - C_e$. We shall use a new

[43] To construct a three-effort example where (A8) is satisfied, consider two values of t, say t_L, t_H, where $0 < t_L < t_H$, and three values of $(\gamma(t), \delta(t))$, say $(\gamma_1, \delta_1), (\gamma_2, \delta_2), (\gamma_3, \delta_3)$. We seek a triple $\Big((C_1, C_2, C_3),\ \{R_s\}_{s=1,\ldots,S},\ (p^1, p^2, p^3)\Big)$ which violates the Approximate-concavity condition and has the following property: $(\gamma(t), \delta(t))$ equals $(3, 3)$ for $0 < t \leq t_L$; equals $(3, 2)$ for $t_L < t \leq t_H$; and equals $(1, 1)$ for $t > t_H$. Then we have a downward jump in $D(\cdot)$ at $t = t_H$.

symbol, namely $\phi(\rho)$ to denote the Agent's chosen effort when the ratio is ρ. So $\phi(\rho) = \hat{e}(r,t)$. In view of (α),(β), and the fact that $\overline{R}^e$ is nondecreasing in e, the function $\rho\overline{R}^e - C_e$ displays strictly increasing differences with respect to ρ, e. Hence (applying (#)) the maximizer $\phi(\rho)$ is nondecreasing in ρ, so we have

$$(A13) \qquad \phi(\rho_H) \geq \phi(\rho_L) \text{ whenever } 0 < \rho_L < \rho_H.$$

We can now reinterpret the Principal as the chooser of a ratio. For a given t, she chooses the ratio $\rho^*(t) = \frac{r^*(t)}{t}$, where

$$\rho^*(t) = \min \ \{\text{argmax}_{\rho \in (0,1/t)} \ M(\rho, -t) \ \},$$

and

$$M(\rho, -t) = (1 - t\rho) \cdot \overline{R}^{\phi(\rho)} = \overline{R}^{\phi(\rho)} - t\rho\overline{R}^{\phi(\rho)}.$$

By (α), the function M has strictly increasing differences in $\rho, -t$ if the function $-t\rho\overline{R}^{\phi(\rho)}$ has strictly increasing differences in $\rho, -t$. Examining $[-t] \cdot \left[\rho \cdot \overline{R}^{\phi(\rho)}\right]$, we see that the first expression in square brackets is strictly increasing in $-t$. The second expression is strictly increasing in ρ, since $\overline{R}^e$ is strictly increasing in e and, by (A13), ϕ is nondecreasing. So we can apply (β). The function $-t\rho\overline{R}^{\phi(\rho)}$ has strictly increasing differences in $\rho, -t$, and so, since $\rho^*(t)$ is a maximizer of $M(\rho, -t)$,

$$(A14) \qquad \frac{r^*(t_L)}{t_L} = \rho^*(t_L) \geq \rho^*(t_H) = \frac{r^*(t_H)}{t_H} \text{ whenever } 0 < t_L < t_H.$$

But $\phi\left(\frac{r^*(t)}{t}\right) = \hat{e}(r^*(t), t)$. That, together with (A13) and (A14), establishes (A12).

As for the claim about $\gamma(\cdot)$, note that the effort $\hat{e}(1,t)$ maximizes $\overline{R}^e - tC_e$. We repeat the easy argument (at the start of section 3.1), showing that surplus-maximizing effort cannot rise when t drops[44]

Step 2: proving that $\delta(\cdot) \leq \gamma(\cdot)$ (no squandering)

In view of (α), (β), the function $r \cdot \overline{R}^e - tC_e$, where t is fixed, displays strictly increasing differences in r and e, since $\overline{R}^e$ is strictly increasing in e. Since, for fixed t, the effort $\hat{e}(r,t)$ maximizes $r \cdot \overline{R}^e - tC_e$, we obtain

$$\hat{e}(r_L, t) \leq \hat{e}(r_H, t) \text{ whenever } 0 < r_L < r_H \leq 1.$$

In particular (since $r^*(t) \leq 1$), we have:

$$\hat{e}(r^*(t), t) \leq \hat{e}(1, t) \text{ for all } t > 0.$$

[44]The term $\hat{e}(1, t_H)$ now plays the role of "e" and $\hat{e}(1, t_L)$ now plays the role of "f".

Since we define $\delta(t), \gamma(t)$, to be, respectively, $\hat{e}(r^*(t), \hat{e}(1,t)$, we have $\delta(t) \leq \gamma(t)$. (The Principal never squanders).

Step 3: completing the proof.

Proposition 1 states that the Penalty is zero for sufficiently small and sufficiently large t. It is straightforward to show that for sufficiently small t we have $r^*(t) = 1$ and hence $\hat{e}(r^*(t), t) = E = \hat{e}(1,t)$, so the Penalty is zero. For sufficiently large t we have $r^*(t) = 0$ and hence $\hat{e}(r^*(t), t) = 1 = \hat{e}(1,t)$, so the Penalty is again zero.

Having shown that the key properties of $\delta(\cdot)$ and $\gamma(\cdot)$ used in the Proposition-1 proof hold again, we now repeat Step 2 of that proof (which uses the assumed Approximate-concavity), as well as Step 3 of that proof.

That completes the proof of Proposition 2. $\square$

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