Chapter 2

INCENTIVES AND THE SEARCH FOR UNKNOWN RESOURCES SUCH AS WATER*

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1. INTRODUCTION

The delegation of discovery tasks is quite common. Researchers are funded by public and private organizations for discovering new theorems, new computer algorithms, new engineering processes. Multinational companies are often delegated the search and exploitation of oil fields or other natural resources such as water. Communities often own in common resources of unknown magnitudes like water, wood, plants, fruits, game in forests or fish in rivers and oceans. In general, communities specialize some individuals (hunters, fishermen) to look for these resources.

Hence most of the R&D efforts are delegated by principals to agents through labor contracts. The R&D literature has well taken into account the randomness of discoveries and the need to structure contracts for giving proper incentives to the agents in charge of R&D tasks. One essential feature of the discovery process which has not been taken into account is that, almost by definition, the nature or size of the discovery is private information of the agent who makes the

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discovery. This may lead to opportunistic behavior of agents. Taking advantage of the "no slavery" conditions of labor contracts, researchers may hide their true discovery, renege on their labor contract and exploit their discovery outside the principal-agent relationship. Companies which are delegated by countries the search for natural resources may take advantage of the lack of technical expertise of these countries to hide some of their discoveries or even flee the country with their discovery. Similarly, hunters or fishermen may hide some of their findings and consume them secretly.

The common structure of these examples is a principal-agent problem in which a principal delegates to an agent the search for a resource of unknown size, and the outcome of the search is partially nonverifiable, and contracts are imperfect. In this paper we study this contractual problem by modelling the imperfection of contracts as an imperfection in the enforcement of contracts combined with limited liability constraints, noticeable characteristics of Less Developed Countries.

Let us illustrate our main findings within the following example. A company is in charge of finding water in the mountains. Part of the discovered water must be piped to the downstream town, the remaining being consumed locally. This sharing problem is made difficult because only the company knows the size of the discovery. Moreover, when the discovery is big enough the company may want to quit the principal-agent relationship to exploit the discovery alone, for example through selling water on a black market. To avoid this outcome, the principal (here the town) has to reward a company announcing a big discovery, thus creating an incentive to lie for companies whose discovery is of a small size. The optimal contract is shown to include unusual distortions: companies with big discoveries should optimally be asked to provide more water to the town than is socially optimal, so as to deter companies with small discoveries to mimic them.

Moreover, in such a regime the principal turns out to be better off when the size of the discovery is smaller. This creates perverse incentives, since the principal may want to discourage the search effort exerted by the agent. In an extension of the model including an endogenous search effort, we show that this is indeed the case. The optimal contract discourages the search effort by rewarding companies announcing small discoveries.

These findings rely on the imperfection of contracts, that is, the town cannot deter a company with a big discovery to turn to the black market if it finds it profitable. The key problem is thus a question of enforcement. We show that with better enforcement more natural incentives are restored. We also discuss by means of examples how the perverse incentives may appear or not, depending on precise properties of the agent's payoffs.

This paper is related to several strands of the economic literature. The first one deals with principal-agent models with interim status-quo payoffs which are state dependent (Lewis and Sappington, 1989; Laffont and Tirole, 1990; Maggi and Rodriguez-Clare, 1995; Jullien, 2000). In our analysis the imperfection of enforcement will yield such interim constraints despite the fact that contracts are signed ex ante. The second one is the law and economics literature initiated by Becker (1968), Stigler (1970), Becker and Stigler (1974) about the imperfect enforcement of laws, rules and contracts. Even though it would be desirable to derive this imperfection from explicit transaction costs of the enforcement mechanism we will adopt a rather ad hoc formulation as in this literature. The third strand of the related literature concerns the manipulation of endowments in mechanism design (Postlewaite, 1979; Hurwicz et al., 1982; Green and Laffont, 1986). However, for reasons to be given below we will not use the major insight of these papers which is to argue that one can only lie downward about endowments.

Section 2 sets up the model and derives the optimal contract under complete information. Section 3 derives the precise structure of the optimal contract under asymmetric information when enforcement is imperfect. This structure implies in Section 4 that the principal has the perverse incentive to discourage the agent's effort for high quality discovery. Section 5 shows how an improvement of enforcement may restore the optimality of contract and reverse these perverse incentives. Various extensions are discussed in Section 6. It is shown in particular that the details of enforcement imperfections matter a lot for the qualitative features of the optimal contract. Concluding comments are gathered in Section 7.

2. THE MODEL

We consider a principal-agent relationship in which a principal delegates to an agent the search for a resource of unknown magnitude. For reference we consider in this section the case where the amount θ of resource is known. This amount must be shared between the principal and the agent.

The principal's utility function is $u(q) - t$, where u is concave, q is the quantity of the resource obtained by the principal, and t is the monetary payment made by the principal to the agent. By symmetry the agent's utility function is $u(\theta - q) + t$. These surpluses may be interpreted as the revenues from selling the resource to final consumers. We normalize these revenues so that $u(0) = 0$.

Under complete information the principal maximizes his utility under the participation constraint of the agent

$$u(\theta - q) + t \geq 0.$$

For each θ the optimal solution $(q^*(\theta), t^*(\theta))$ is characterized by equal sharing of the good $q^*(\theta) = \theta/2$, with $t^*(\theta) = -u\left(\frac{\theta}{2}\right)$.

3. OPTIMAL CONTRACT UNDER ASYMMETRIC INFORMATION

The amount discovered θ is now private information of the agent. θ can take two values $\underline{\theta}$ and $\bar{\theta}$ with respective probabilities $1-\nu$ and ν. Let $\Delta\theta$ denote the difference $\bar{\theta}-\underline{\theta}$. From the revelation principle we can focus on incentive compatible menus of contracts $\{\underline{t}, \underline{q}; \bar{t}, \bar{q}\}$, verifying the following two incentive compatibility constraints

$$u(\bar{\theta}-\bar{q})+\bar{t} \geq u(\bar{\theta}-\underline{q})+\underline{t} \tag{1}$$
$$u(\underline{\theta}-\underline{q})+\underline{t} \geq u(\underline{\theta}-\bar{q})+\bar{t}. \tag{2}$$

The contract between the principal and the agent is signed at the ex ante stage and subject to the agent's ex ante participation constraint:

$$\nu(u(\bar{\theta}-\bar{q})+\bar{t})+(1-\nu)(u(\underline{\theta}-\underline{q})+\underline{t}) \geq 0. \tag{3}$$

Furthermore, we assume that they are some enforcement difficulties originating in the legal environment. Firstly, the agent is protected by limited liability, and cannot end up with a negative payoff. Secondly, we suppose that at any time the agent can quit the principal-agent relationship[1] and exploit the discovery by himself. In such a case courts can only impose that the amount $\underline{\theta}$ is left to the Principal. Hence, if the agent discovers a high amount $\bar{\theta}$, he can disappear with the amount $\Delta\theta$ of the resource, thus getting the payoff $w \equiv u(\Delta\theta)$. This leads to the additional enforcement constraints:

$$\underline{U} = u(\underline{\theta}-\underline{q})+\underline{t} \geq 0 \tag{4}$$
$$\bar{U} = u(\bar{\theta}-\bar{q})+\bar{t} \geq w. \tag{5}$$

The principal's best menu of contracts maximizes, under (1) to (5) the following objective function:[2]

$$\nu(u(\bar{q})-\bar{t})+(1-\nu)(u(\underline{q})-\underline{t}). \tag{6}$$

In the absence of enforcement constraints, the principal facing a risk neutral agent with an ex ante participation constraint would achieve his first-best.[3] Note also that (3) is implied by (4) and (5), so that the only constraints to consider are (1) (2) (4) (5). The problem then becomes similar to a principal agent problem with interim participation constraints and type-dependent status-quo utility levels for the agent.[4]

Appendix A derives the shape of the optimal contract for arbitrary values for w. It is shown that $\underline{q}$ must be *distorted downward* (below the first-best level $q^*(\underline{\theta}) = \underline{\theta}/2$), while $\bar{q}$ must be *distorted upward* (above $q^*(\bar{\theta}) = \bar{\theta}/2$). The point we would like to underline is the following. For $w = u(\Delta\theta)$, the usual result that the incentive constraint (1) and the enforcement constraint (4) are binding does not hold anymore. Indeed the rent of the "good" type $\bar{\theta}$ would be equal to

$$u(\bar{\theta}-\bar{q})+\bar{t}=u(\bar{\theta}-\underline{q})+\underline{t}=u(\bar{\theta}-\underline{q})-u(\underline{\theta}-\underline{q})$$
$$=u(\Delta\theta+\underline{\theta}-\underline{q})-u(\underline{\theta}-\underline{q})<u(\Delta\theta)=w$$

where the last inequality comes from the concavity of u and the fact that $\underline{q}<\underline{\theta}$. Thus (5) would not hold. We are then led to distinguish between three regimes.

Regime 1: this regime obtains when only the enforcement constraints are binding. Substituting these constraints in the principal's objective function and maximizing with respect to $\underline{q}$, $\bar{q}$, we obtain efficient sharing. In this case, the principal's expected welfare is

$$W_1=2\nu u\left(\frac{\bar{\theta}}{2}\right)+2(1-\nu)u\left(\frac{\underline{\theta}}{2}\right)-\nu u(\Delta\theta).$$

With respect to the first best, the principal loses only $\nu u(\Delta\theta)$. Such a contract is optimal as soon as it verifies the constraint (2), or equivalently if $\Delta\theta\geq\underline{\theta}$.

In the other two regimes we have countervailing incentives, i.e., it is the incentive constraint (2) of the "bad" type $\underline{\theta}$ which is binding.

Regime 3: the enforcement constraint of the good type $\bar{\theta}$ and the incentive constraint of the bad type $\underline{\theta}$ are binding. Optimizing quantities we get:

$$\underline{q}_3 = q^*(\underline{\theta})=\frac{\underline{\theta}}{2} \tag{7}$$

$$u'(\bar{q}_3) = u'(\bar{\theta}-\bar{q}_3)-\frac{(1-\nu)}{\nu}\left(u'(\underline{\theta}-\bar{q}_3)-u'(\bar{\theta}-\bar{q}_3)\right). \tag{8}$$

The principal's expected welfare is then

$$\begin{aligned} W_3 &= \nu(u(\bar{q}_3)+u(\bar{\theta}-\bar{q}_3))-\nu u(\Delta\theta) \\ &\quad +2(1-\nu)u\left(\frac{\underline{\theta}}{2}\right)-(1-\nu)\left(u(\Delta\theta)-(u(\bar{\theta}-\bar{q})-u(\underline{\theta}-\underline{q}))\right). \end{aligned}$$

However, this case is valid only if the $\underline{\theta}$ agent's participation constraint is satisfied :

$$u(\Delta\theta)-(u(\bar{\theta}-\bar{q}_3)-u(\underline{\theta}-\bar{q}_3))\geq 0$$

i.e., if $\bar{q}_3\leq\underline{\theta}$.

If $\bar{q}_3>\underline{\theta}$, we have **Regime 2** which connects Regimes 1 and 3. In Regime 2, $\bar{q}_2=\underline{\theta}$ and $\underline{q}_2$ still equates $\frac{\underline{\theta}}{2}$ with both enforcement constraints binding and defining the transfers. Then, the principal's expected welfare is

$$W_2 = \nu u(\underline{\theta}) + 2(1-\nu)u\left(\frac{\underline{\theta}}{2}\right).$$

Summarizing we have:

PROPOSITION 1: *Suppose that $w = u(\Delta\theta)$. The optimal menu of contracts entails:*

i) Efficient sharing if the asymmetry of information is large enough ($\Delta\theta > \underline{\theta}$).

ii) Countervailing incentives and ***upward*** *distortions of the quantity allocated to the $\bar{\theta}$-agent, otherwise.*

For the example $u(x) = x - \frac{x^2}{2}$ we give in Figure 1 the typical profile of quantity allocated to the $\bar{\theta}$-agent.

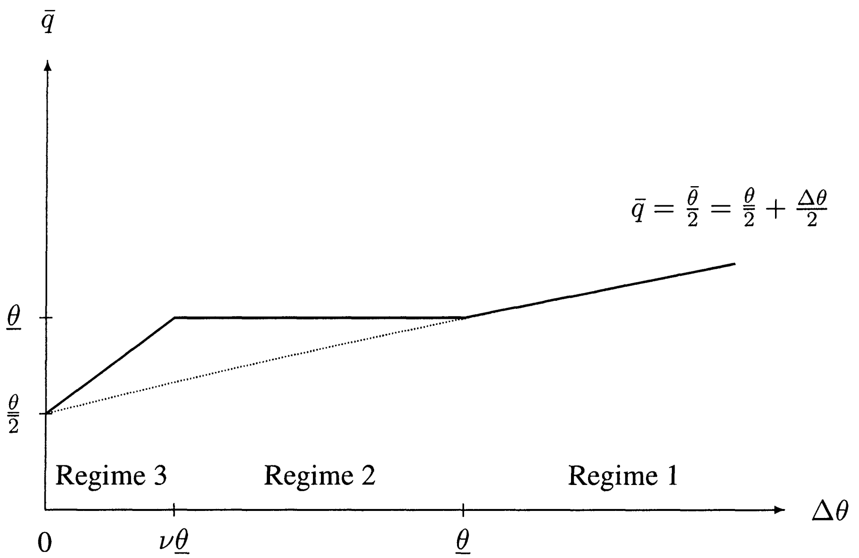

Figure 1. Typical profile of quantity allocated to the $\bar{\theta}$-agent

So far, the main implication of enforcement constraints is that they may yield unexpected distortions of the optimal contract. For w high enough (and in particular for $w = u(\Delta\theta)$), the enforcement constraint (5) requires that the principal offers type $\bar{\theta}$ a contract so favorable that it becomes attractive to the $\underline{\theta}$-type. This calls for a distortion of the $\bar{\theta}$-contract aimed at avoiding this mimicking behavior, namely an *upward* distortion (with respect to the first-best) in the quantity that $\bar{\theta}$ must provide. In the next section, we shall see that these characteristics of the optimal contract have surprising effects on the principal's incentives to favor large discoveries.

4. INCENTIVES FOR DISCOVERY EFFORT

One consequence of the derivations above is that the Principal may be better off when the discovery is small. Indeed define the Principal's payoffs as

$$\underline{V} = u(\underline{q}) - \underline{t} \qquad \bar{V} = u(\bar{q}) - \bar{t}.$$

In regimes 2 and 3, the incentive constraint (2) is binding. Replacing we get

$$\bar{V} - \underline{V} = u(\bar{q}) + u(\underline{\theta} - \bar{q}) - u(\underline{q}) - u(\underline{\theta} - \underline{q})$$

which is easily shown to be negative.[5] This shows that the Principal gets a higher payoff when the discovery is small.

The same result holds also in Regime 1, where the welfare obtained by the principal is

$$W_1(\nu) \equiv 2\left(\nu u\left(\frac{\bar{\theta}}{2}\right) + (1-\nu)u\left(\frac{\underline{\theta}}{2}\right)\right) - \nu u(\Delta\theta)$$

which is decreasing in ν from the concavity of u. Once more, the Principal gets a higher payoff when the discovery is small. This surprising result calls for a precise study of the agent's search effort, and of the incentives for effort given by the contract.

So far, the agent was unable to affect by his own behavior the probability distribution of the discovery size. We assume now that by exerting an effort which costs him ψ the agent increases the probability of a $\bar{\theta}$-discovery from ν_0 to $\nu_1 > \nu_0$ and let $\Delta\nu = \nu_1 - \nu_0$.

Because intuitively the principal wishes to discourage the agent from making an effort, let us first solve our program under the constraint that the agent exerts no effort:

$$\max_{(\bar{q},\bar{t};\underline{q},\underline{t})} \nu_0(u(\bar{q}) - \bar{t}) + (1-\nu_0)(u(\underline{q}) - \underline{t})$$

under (1)(2)(4)(5) and

$$\begin{aligned}\nu_0(u(\bar{\theta} - \bar{q}) + \bar{t}) &+ (1-\nu_0)(u(\underline{\theta} - \underline{q}) + \underline{t}) \\ &\geq \nu_1(u(\bar{\theta} - \bar{q}) + \bar{t}) + (1-\nu_1)(u(\underline{\theta} - \underline{q}) + \underline{t}) - \psi. \qquad (9)\end{aligned}$$

This last constraint can be rewritten as

$$\bar{U} - \underline{U} \leq \frac{\psi}{\Delta\nu}.$$

In Regimes 1, 2 and 3, the left-hand-side was anyway less than $w = u(\Delta\theta)$. We therefore obtain that if $u(\Delta\theta) < \frac{\psi}{\Delta\nu}$, the principal does not need to distort the solution found in the preceding section: the rent differential is low compared to the cost of effort. Then, the principal obtains the expected welfare $W_1(\nu_0)$.

In Appendix B, we show that when $\Delta\theta$ increases, the principal increases the rent $\underline{U}$ of the $\underline{\theta}$-type to still discourage effort. For $\Delta\theta$ large, the principal gives up discouraging the agent from exerting effort and obtains the expected welfare $W_1(\nu_1)$.

We summarize these results by the following proposition. Figure 2 illustrates the impact of $\Delta\theta$ on the Principal's payoff.

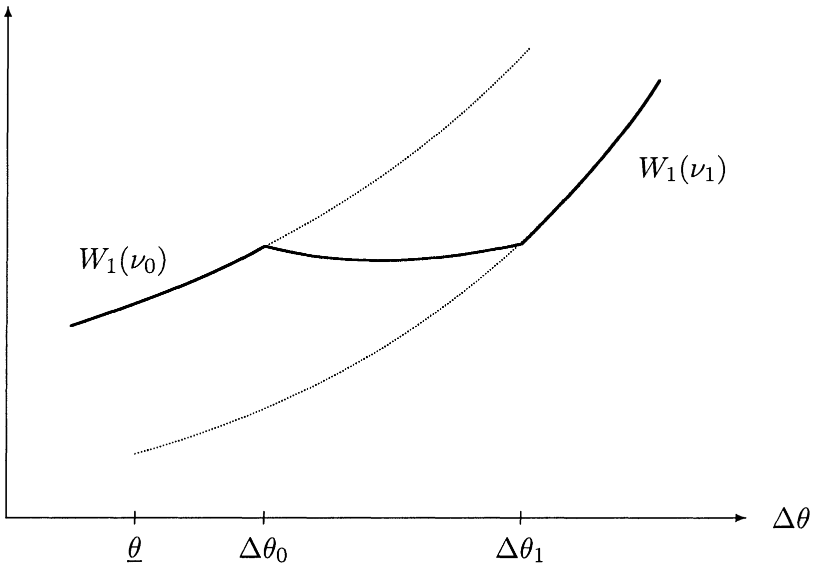

Figure 2. Impact of $\Delta\theta$ on the Principal's payoff

PROPOSITION 2: *Suppose that $w = u(\Delta\theta)$. The principal will structure incentives in order to discourage effort. This is done without cost for small $\Delta\theta$. For large $\Delta\theta$ he gives up discouraging effort. For intermediary values of $\Delta\theta$ discouraging effort is costly and requires rewarding more the $\underline{\theta}$-agent.*

The striking consequence of the enforcement constraint is that the principal has the incentive to discourage effort. If possible he will even make difficult for the agent to increase his probability of a high discovery, by denying for example proper equipment. He will also structure incentive payments so that effort is discouraged, unless it is too costly. Not only is weak enforcement calling for distortions in general and is costly to the principal. It can set up very wrong incentives for progress in society.

The intuition for this result is simply that the principal benefits more from a $\underline{\theta}$-agent than from a $\bar{\theta}$-agent because of the cost of the enforcement constraint, as was shown at the beginning of this Section. In the next section we show how an improvement of enforcement may take the relationship out of the vicious circle emphasized above.

5. ENDOGENOUS ENFORCEMENT

Suppose now that with an ex ante expense of $c(p)$ the principal can improve enforcement. More specifically, with probability p the agent is set at the zero utility level[6] and with probability $1-p$ he escapes. Let us assume that $c(\cdot)$ is convex with the Inada conditions $c(0)=0$, $c'(0)=0$, $\lim_{p\to 1} c'(p)=\infty$.

The ex post enforcement constraint (5) becomes

$$\bar{U} = u(\bar{\theta}-\bar{q}) + \bar{t} \geq (1-p)u(\Delta\theta). \tag{10}$$

The principal's problem can be rewritten

$$\max_{\{\bar{q},\bar{t};\underline{q},\underline{t};p\}} \nu(u(\bar{q})-\bar{t}) + (1-\nu)(u(\underline{q})-\underline{t}) - c(p)$$

s.t. (1) (2) (4) (10).

Thanks to enforcement expenditures it is now possible to have Regime 0, for which the $\bar{\theta}$-type incentive constraint and the $\underline{\theta}$-participation constraint are binding. Actually, it is never worth spending enforcement resources to make constraint (10) strict. So, in Regime 0, constraints (1) (3) (10) are binding. Substituting the transfers from (1) and (3) into the principal's objective function leads to:

$$\begin{aligned}\max_{\{\bar{q},\underline{q},p\}} \quad & \nu\left(u(\bar{q}) + u(\bar{\theta}-\bar{q}) - (u(\bar{\theta}-\underline{q}) - (\underline{\theta}-\underline{q}))\right) \\ & +(1-\nu)(u(\underline{q}) + u(\underline{\theta}-\underline{q})) - c(p)\end{aligned}$$

s.t.

$$u(\bar{\theta}-\underline{q}) - u(\underline{\theta}-\underline{q}) - (1-p)u(\Delta\theta) = 0.$$

The optimal solution is:

$$\begin{aligned}\bar{q}_0 &= \frac{\bar{\theta}}{2} & (11)\\ u'(\underline{q}_0) &= u'(\underline{\theta}-\underline{q}_0) - \frac{\left(\nu - \frac{c'(p_0)}{u(\Delta\theta)}\right)}{1-\nu}\left(u'(\bar{\theta}-\underline{q}_0) - u'(\underline{\theta}-\underline{q}_0)\right) & (12)\\ u(\bar{\theta}-\underline{q}_0) &- u(\underline{\theta}-\underline{q}_0) = (1-p_0)u(\Delta\theta). & (13)\end{aligned}$$

This solution holds as long as the $\underline{\theta}$-agent's incentive constraint is not binding (i.e., for $\bar{\theta} > 2\underline{\theta}$) and as long as $c'(p_0) < \nu u(\Delta\theta)$. We observe that the enforcement cost leads to a smaller distortion in $\underline{q}_0$. Indeed, when $\underline{q}_0$ is decreased to decrease the $\bar{\theta}$-agent's information rent one must take into account the addition enforcement cost due to the higher p_0 needed to maintain (13).

When $\Delta\theta$ decreases and p_0 reaches p_1 defined by $c'(p_0) = \nu u(\Delta\theta)$, the $\bar{\theta}$-agent's incentive constraint becomes slack and we obtain Regime 1 with efficient sharing $p = p_1$ and transfers $\underline{t} = -u\left(\frac{\underline{\theta}}{2}\right)$, $\bar{t} = -u\left(\frac{\bar{\theta}}{2}\right) + (1 - p_1)u(\Delta\theta)$. When $\bar{\theta} < 2\underline{\theta}$, we have also two regimes. In Regime 3, only the participation constraint of type $\bar{\theta}$ and the incentive constraint of type $\underline{\theta}$ are binding. We obtain immediately

$$\underline{q}_3 = \frac{\underline{\theta}}{2} \tag{14}$$

$$u'(\bar{q}_3) = u'(\bar{\theta} - \bar{q}_3) - \frac{(1-\nu)}{\nu}\left(u'(\underline{\theta} - \bar{q}_3) - u'(\bar{\theta} - \bar{q}_3)\right) \tag{15}$$

$$c'(p_3) = u(\Delta\theta). \tag{16}$$

For $\Delta\theta$ higher p is adjusted so that

$$(1-p)u(\Delta\theta) = u(\bar{\theta} - \bar{q}) - u(\underline{\theta} - \underline{q})$$

and we obtain Regime 2 characterized by

$$\underline{q}_2 = \frac{\underline{\theta}}{2} \tag{17}$$

$$u'(\bar{q}_2) = u'(\bar{\theta} - \bar{q}_2) + \frac{\left(1 - \nu - \frac{c'(p_2) - u(\Delta\theta)}{u(\Delta\theta)}\right)}{\nu} \cdot \left(u'(\bar{\theta} - \bar{q}_2) - u'(\underline{\theta} - \bar{q}_2)\right) \tag{18}$$

$$(1-p_2)u(\Delta\theta) = u(\bar{\theta} - \bar{q}_2) - u(\underline{\theta} - \underline{q}_2). \tag{19}$$

Putting together these results we describe in Figure 3 the profile of optimal enforcement levels. For the quadratic example we obtain in Figure 4 the quantity profiles.

When better enforcement produces Regime 0, the principal's welfare becomes increasing in ν and the principal has now incentives to induce effort. For a given level of ψ they may not want to pay the price for it, but as $\Delta\theta$ increases they will indeed structure the incentives to induce effort.

Summarizing we have:

PROPOSITION 3: *When the cost of better enforcement is low enough the principal becomes interested in increasing ν for $\Delta\theta$ large enough. He will then structure incentives to induce effort.*

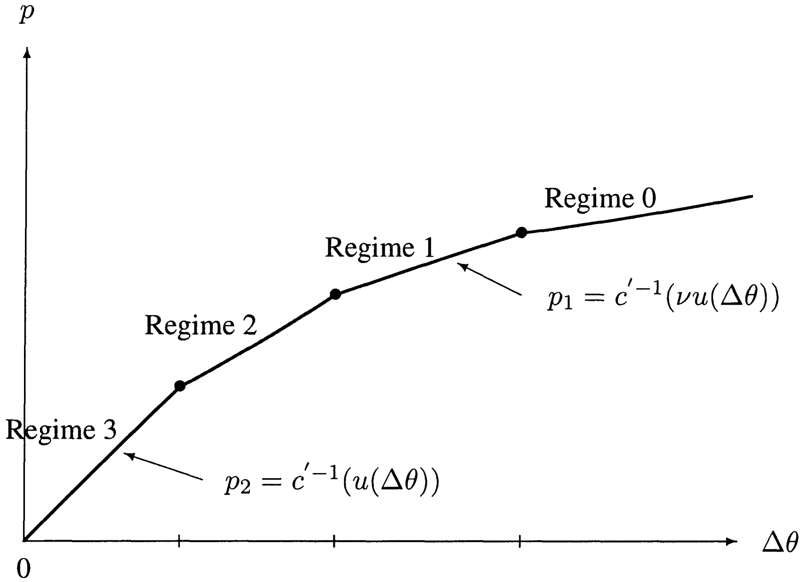

Figure 3. Profile of optimal enforcement levels

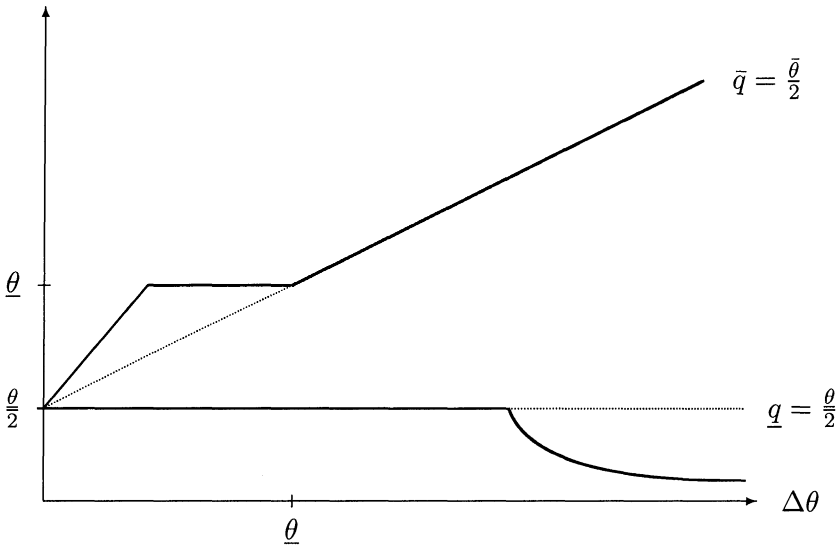

Figure 4. Quantity profiles for the quadratic example

Note that better enforcement and lower powered incentives for production are complement instruments. Indeed, better enforcement creates higher incentives for discovery effort. This in turn creates a higher probability of having a $\bar{\theta}$-agent, therefore a higher desire to limit his information rent through a lower powered incentives for production.

6. EXTENSIONS

One could argue that the agent can hide some of his discovery, but cannot claim he has discovered more than he has done in reality, because he must be able to show it. In other words, he can lie downward but not upward.[7]

In this case, there is no incentive constraint for the $\underline{\theta}$-type, and the only binding constraints are the participation constraints with efficient sharing of the discovered resource.

However, there are cases where such a strategy of asking the agent to exhibit his discovery is not possible. If it is a discovery like a computer program, just showing it provides the resource to the principal. If it is a farmer upstream on a river the water he let flow downstream cannot be recaptured. Also the agent may have hidden resources which enable him to mimic the behavior of the $\bar{\theta}$-type. The model we have studied is designed to fit those situations. The next paragraphs offer some extensions.

6.1 Modelling Imperfect Enforcement

It turns out that the details of imperfect enforcement play a crucial role in determining the structure of the optimal contract and its impact on the incentives for discovery effort.

Let us denote more generally $w(\theta)$ the outside opportunity of type θ when he reneges on the contract. If we still normalize $w(\underline{\theta}) = 0$ we have the "normal" case of Regime 0 if

$$u(\bar{\theta} - \underline{q}^{SB}) - u(\underline{\theta} - \underline{q}^{SB}) > w(\bar{\theta})$$

where $\underline{q}^{SB}$ is determined by

$$u'(\underline{q}^{SB}) = u'(\underline{\theta} - \underline{q}^{SB}) - \frac{\nu}{1-\nu}\left(u'(\bar{\theta} - \underline{q}^{SB}) - u'(\underline{\theta} - \underline{q}^{SB})\right).$$

We saw above that it is impossible if $w(\bar{\theta}) = u(\bar{\theta} - \underline{\theta})$ and that it can become possible if $w(\bar{\theta}) = (1-p)u(\bar{\theta} - \underline{\theta})$ for p large enough.

An alternative formulation is

$$w(\theta) = (1-p)u(\theta) \qquad \text{for all } \theta.$$

Then, the rent of a good type verifies

$$u(\underline{\theta}) + u(\bar{\theta} - \underline{q}^{SB}) - u(\underline{\theta} - \underline{q}^{SB}) \geq u(\bar{\theta}) \geq (1-p)u(\bar{\theta}),$$

since $u(\bar{\theta} - q) - u(\underline{\theta} - q)$ is increasing in q. We always have Regime 0.

It is therefore important to understand how the imperfection of enforcement structures the outside opportunity levels of the reneging agents. We give below a few examples:

i) Black market.
Suppose that, when they carry out their contract, the principal and the agent can sell their share of the product on a idiosyncratic market each with the inverse demand function $P(\cdot)$ with $P(q)q$ concave.

Then

$$\begin{aligned} u(q) &= P(q)q \\ u(\theta - q) &= P(\theta - q)(\theta - q). \end{aligned}$$

Alternatively the agent may renege the contract and sell on a black market with the inverse demand function $\tilde{P}(\cdot)$. This provides an alternative revenue of $\tilde{P}(\theta)\theta$ or $(1-p)\tilde{P}(\theta)\theta$ if the agent is caught with probability p.

Again, Regime 0 cannot hold if

$$\tilde{P}(\underline{\theta})\underline{\theta} + P(\bar{\theta} - \underline{q}^{SB})(\bar{\theta} - \underline{q}^{SB}) - P(\underline{\theta} - \underline{q}^{SB})(\underline{\theta} - \underline{q}^{SB}) \leq \tilde{P}(\bar{\theta})\bar{\theta}.$$

In words it means simply that the information rent

$$P(\bar{\theta} - \underline{q}^{SB})(\bar{\theta} - \underline{q}^{SB}) - P(\underline{\theta} - \underline{q}^{SB})(\underline{\theta} - \underline{q}^{SB})$$

must be less than the difference of opportunities in the black market between the two types of agents. Clearly, all cases are possible depending on the demand function in the black market.

ii) Corruption of enforcer.
Suppose that leaving the country is only possible through corruption of the customs officer; and suppose that a minimal bribe of k in units of the good is needed to corrupt the officer. Assume $\underline{\theta} < k$. Then

$$\begin{aligned} w(\underline{\theta}) &= 0 \\ w(\bar{\theta}) &= u(\bar{\theta} - k). \end{aligned}$$

This yields a model analogous to the one studied above. Clearly, the details of the corruption game are crucial. For example, the agent might need the complicity of the officer to value the good and would have to share the good. Let α be the share of the agent, so that

$$w(\theta) = u(\alpha\theta).$$

Then for α large enough, Regime 0 cannot hold while it does if α is small enough.

iii) Joint Venture.
Suppose that to value his discovery the agent must pay a fixed cost k, that his principal and maybe others have already sunk.

Then $w(\theta) = u(\theta) - k$. The principal can implement Regime 0 and the more cheaply the larger is k. However, if other "principals" have also sunk the fixed cost, the agent may still renege and organize an auction between the principals. This would be the case of a researcher paid in his university to do research and who, after a large $\bar{\theta}$ discovery, would take advantage of the "no slavery" constraint in labor contracts to leave and offer his discovery to other universities. This illustrates the kind of inefficiency which may arise due to the "no slavery" condition.[8]

6.2 Continuous Case

The analysis can be easily extended to the case of continuous type θ in $[\underline{\theta}, \bar{\theta}]$. The objective function of the agent is then

$$U(\theta) = u(\theta - q(\theta)) + t(\theta)$$

resulting in an incentive constraint (for Regime 0)

$$\dot{U}(\theta) = u'(\theta - q(\theta)).$$

It is then easy to see that Regime 0 is impossible if the slope of the information rent $u'(\theta - q(\theta))$ is lower than the slope of the outside opportunity $w'(\theta)$.

For example, if $w'(\theta) = (1-p)u'(\theta)$

$$u'(\theta - q(\theta)) > (1-p)u'(\theta)$$

and Regime 0 always occur. If $w'(\theta) = u'(\theta - \underline{\theta})$ then for θ small,

$$u'(\theta - \bar{q}(\theta)) < u'(\theta - \underline{\theta})$$

as $q(\theta) < \theta$ for θ in a neighborhood of $\underline{\theta}$. Then Regime 0 is impossible for θ close to $\underline{\theta}$. For large θ it becomes possible (see Appendix C).

So what matters are not the absolute levels of information rents and outside opportunities, but their rate of growth in the parameter of asymmetric information.

7. CONCLUSION

We have studied a delegation problem in which the nonverifiability of the agent's discovery fuels the opportunistic behavior of agents who have high performances and may renege on their contract and value their discovery outside the principal-agent relationship. A striking implication of the optimal contract is that it may destroy the incentive of the principal to provide good working conditions to the agent which would increase the probability of high discovery, and even favor the reward for low discovery to discourage agents to exert high levels of effort which would increase this probability of high discovery. Then, we have shown how an improvement of institutions in the form of better enforcement of contract, brought about by computer equipment for example, may reverse those perverse incentives. Finally, we have shown the need for a deeper analysis of the transaction costs of contract enforcement whose details affect considerably the structure of the optimal contract and the incentives it creates.

Beyond this main point, our analysis calls for further research in various directions. One is in labor economics and R&D research where the traditional "no slavery" conditions which make easy for workers to end their employment relationship may have spectacular implications on incentives.

Another is the analysis of the impact of black markets on the structure of labor contracts in the formal economy. Also, it would be interesting to characterize the optimal auctions of contracts for discovery of resources when the nonverifiability and enforcement conditions of this paper hold.

Appendix A

The problem may be solved directly. Define

$$\varphi(q) = u(\bar{\theta} - q) - u(\underline{\theta} - q)$$

which is positive and increasing due to the concavity of u. The constraints may be rewritten

$$\underline{U} \geq 0 \qquad \bar{U} \geq w \qquad \varphi(\bar{q}) \geq \bar{U} - \underline{U} \geq \varphi(\underline{q})$$

Because the principal tries to reduce the rents, we get

$$\bar{U} = \max(w, \underline{U} + \varphi(\underline{q}))$$

and the constraints reduce to

$$\underline{U} \geq 0 \qquad \underline{U} \geq w - \varphi(\underline{q}) \qquad \varphi(\bar{q}) \geq \varphi(\underline{q})$$

from which we get

$$\underline{U} = \max(0, w - \varphi(\bar{q}))$$

and finally

$$\bar{U} = \max(w, \varphi(\underline{q})).$$

Hence the program reduces to

$$\nu\left[u(\bar{q})+u(\bar{\theta}-\bar{q})-\tfrac{1-\nu}{\nu}\max(0,w-\varphi(\bar{q}))\right]$$
$$+(1-\nu)\left[u(\underline{q})+u(\underline{\theta}-\underline{q})-\tfrac{\nu}{1-\nu}\max(w,\varphi(\underline{q}))\right]$$

to be maximized under $\bar{q} \geq \underline{q}$. In fact, the constraint can be ignored because maximization of each bracket yields $\bar{q} \geq q^*(\bar{\theta})$ and $\underline{q} \leq q^*(\underline{\theta})$. Notice that each bracket is concave in the example $u(x) = x - x^2/2$, because then φ is linear.

In the particular case $w = u(\Delta\theta)$, it is easily seen that the second bracket is maximized at $\underline{q} = q^*(\underline{\theta})$, which indeed verifies $\varphi(\underline{q}) \leq w$. A similar result holds for the first bracket if $\Delta\theta \geq \underline{\theta}$ (Regime 1). Otherwise one can solve

$$\max_{q}\ u(\bar{q})+u(\bar{\theta}-\bar{q})-\frac{1-\nu}{\nu}(w-\varphi(\bar{q}))$$

whose solution $\bar{q}_3$ may be such that $\varphi(\bar{q}_3) \leq w$ (Regime 3), or $\varphi(\bar{q}_3) > w$, and then we have Regime 2.

Appendix B

We can proceed as in Appendix A, taking into account the additional constraint

$$\bar{U}-\underline{U} \leq \frac{\psi}{\Delta\nu}.$$

We still have

$$\bar{U} = \max(w, \underline{U}+\varphi(\underline{q}))$$

and the constraints reduce to

$$\underline{U} \geq 0 \qquad \underline{U} \geq w-\varphi(\underline{q}) \qquad \varphi(\bar{q}) \geq \varphi(\underline{q})$$
$$\underline{U} \geq w-\frac{\psi}{\Delta\nu} \qquad \varphi(\underline{q}) \leq \frac{\psi}{\Delta\nu}$$

from which we get

$$\underline{U} = \max(0, w-\varphi(\bar{q}), w-\frac{\psi}{\Delta\nu})$$

and finally

$$\bar{U} = \max(w, \varphi(\underline{q})).$$

Hence the program reduces to

$$\nu \left[u(\bar{q}) + u(\bar{\theta} - \bar{q}) - \frac{1-\nu}{\nu} \max(0, w - \varphi(\bar{q}), w - \varphi(\underline{q}) \leq \frac{\psi}{\Delta\nu}) \right]$$

$$+(1-\nu) \left[u(\underline{q}) + u(\underline{\theta} - \underline{q}) - \frac{\nu}{1-\nu} \max(w, \varphi(\underline{q})) \right]$$

to be maximized under $\bar{q} \geq \underline{q}$ and $\varphi(\underline{q}) \leq \frac{\psi}{\Delta\nu}$. Once more, the first constraint can be ignored. Compared to Appendix A, the new term in the first bracket tends to reduce $\bar{q}$; the second constraint also reduces $\underline{q}$, compared to the solution in Appendix A.

Appendix C: The continuous type case

Similar insights can be gained in the case where θ belongs to an interval $[\underline{\theta}, \bar{\theta}]$ and is distributed according to the distribution $F(\theta)$ with a positive density $f(\cdot)$. We also assume the hazard rate properties

$$\frac{d}{d\theta}\frac{F(\theta)}{f(\theta)} \geq 0 \quad \text{and} \quad \frac{d}{d\theta}\frac{1-F(\theta)}{f(\theta)} \leq 0$$

to avoid bunching of a classical type.

It is easily shown that with an enforcement constraint of the type

$$U(\theta) \geq (1-p)u(\theta) \tag{C. 1}$$

we have no countervailing incentives.

PROPOSITION 4: *With the enforcement constraint (C. 1) the optimal contract entails downward distortion characterized by:*

$$u'(q^*(\theta)) = u'(\theta - q^{SB}(\theta)) - \frac{1-F(\theta)}{f(\theta)} u''(\theta - q^{SB}(\theta))$$

and a rent

$$U = (1-p)u(\underline{\theta}) + \int_{\underline{\theta}}^{\theta} u'(\tau - q^{SB}(\tau))d\tau.$$

Enforcement constraints simply oblige the principal to give up an additional rent $(1-p)u(\underline{\theta})$ to each type.

With the enforcement constraint

$$U(\theta) \geq u(\theta - \underline{\theta}) \tag{C. 2}$$

one must distinguish two cases.

For $\Delta\theta$ small (more precisely for $\Delta\theta$ such that the solution $q(\theta)$ of the equation below is such that $q(\theta) < \underline{\theta}$) we have countervailing incentives.

PROPOSITION 5: *Under the enforcement constraint (C. 2), we have:*

- *For θ in $[\underline{\theta}, \theta_0]$, production $q_3(\theta)$ is upward distorted.*
- *For θ in $[\theta_0, \theta_1]$, there is bunching and $q_2(\theta) = \underline{\theta}$.*
- *For θ in $[\theta_1, \bar{\theta}]$, production $q_1(\theta)$ is downward distorted.*

Rents are

$$\begin{aligned} U(\theta) &= \int_{\underline{\theta}}^{\theta} u'(\tau - q_3(\tau))d\tau \text{ for } \theta \text{ in } [\underline{\theta}, \theta_0] \\ &= u(\theta - \underline{\theta}) \text{ for } \theta \text{ in } [\theta_0, \theta_1] \\ &= u(\bar{\theta}) - \int_{\theta}^{\bar{\theta}} u'(\tau - q(\tau))d\tau \text{ for } \theta \text{ in } [\theta_1, \bar{\theta}]. \end{aligned}$$

The main difference between the two types of enforcement constraints is as follows.

For (C. 1), the marginal utility of the resource is lower for the agent when for the principal. The solution entails simply a bonus for the agent which is paid each time there is a discovery whatever its value.

For (C. 2), the marginal utility of the resource is higher for the agent. Then, for discoveries of small variance, countervailing incentives prevail and lead to decrease the share of the resource left to the agent to increase his marginal utility for the good and decrease his rent.

For greater variance of discoveries, for which the marginal utility of the resource for the agent is higher and then lower than for the principal as θ increases, we have a complex solution sharing the features of the two cases above as θ increases with a bunching region in between.

Figure 5 describes the profile of quantities.[9]

$$\begin{aligned} u'(q_3(\theta)) &= u'(\theta - q_3(\theta)) + \frac{F(\theta)}{f(\theta)} u''(\theta - q_3(\theta)) \\ u'(q_0(\theta)) &= u'(\theta - q_0(\theta)) - \frac{1 - F(\theta)}{f(\theta)} u''(\theta - q_0(\theta)). \end{aligned}$$

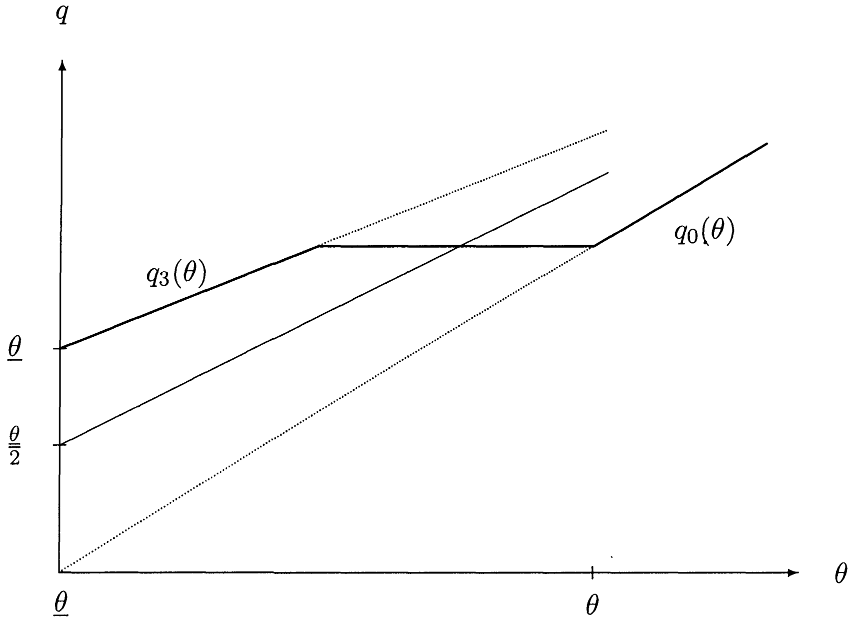

Figure 5. Profile of quantities in a continuous type case

Notes

1. The principal could avoid this ex post opportunistic behavior by requiring a bond which would be lost if reneging occurred. However the lack of wealth of the agent makes this strategy impossible.

2. We assume parameter values such that it is never in the principal's interest to opt for the shutdown of type $\underline{\theta}$ or for giving up the enforcement of type $\bar{\theta}$'s contract.

3. See for example Laffont and Martimort (2002), Chapter 2.

4. See Lewis and Sappington (1989), Maggi and Rodriguez (1995), Jullien (2000), and Laffont and Martimort (2002), Chapter 3 for a simple exposition.

5. Indeed define $g(q) = u(q) + u(\underline{\theta} - q)$. We have $\bar{V} - \underline{V} = g(\bar{q}) - g(\underline{q})$. Notice that $g(q)$ is decreasing for $q \geq \underline{\theta}/2$. The conclusion follows from $\bar{q} > \underline{q} = \underline{\theta}/2$ in regime 2 and 3.

6. Higher penalties are not possible because of limited liability constraints.

7. When the message space available to an agent depends on his type, the revelation principle may not hold (Green and Laffont, 1986). However, our simple case satisfies the necessary and sufficient condition obtained in Green and Laffont (1986) for the revelation principle to hold (see also Bull and Watson, 2001). The literature on manipulation of endowments (Postlewaite, 1979; Hurwicz et al., 1982) makes a crucial use of the inability to lie upward.

8. As labor contracts do not allow for such bonds, firms or universities often circumvent partially this problem by complementing the salary with financial advantages (like mortgage loans) which result in high penalties if the employment relationship is broken.

9. Additional assumptions are needed to avoid bunching when $u''(\cdot)$ is not constant.

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