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MORAL HAZARD WITH COST AND REVENUE SIGNALS

by

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ABSTRACT

A risk neutral principal hires a risk averse agent to produce quality which is unobservable by the principal but generates a random stream of observable revenues. Unobservable effort and some other input called capital costs are perfect complements in the product of quality. The minimum level of capital costs required to produce a particular level of quality is random but provides a signal of agent effort. In particular agent effort serves to increase both expected capital costs and expected revenues. We assume that the principal offers a contract which specifies a set of linear revenue and capital cost shares and then examine how the correlation between capital costs and revenues determines whether the agent is rewarded or punished for incurring high capital costs.

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INTRODUCTION

The motivation for this paper arose from discussions with academics concerning whether successful grant applications should be counted as a measure of performance. There are three views that one can take. First is the double-counting view which says that successful grant applications result in publications and only the later should be counted, otherwise double-counting occurs. The double-counting view thus implies that the successful grant application should get a zero weighting. A second view is the input view which contends that grants are inputs in the production of publications and thus should be given a negative weighting. A final view is the output view which states that grant applications themselves reflect research and thus should be given a positive weighting. If one presumes that the *measuring* of research output is done for the purpose of compensation and *encouraging* research effort and sharing risk then it is not at all clear which of the three views is appropriate.

One characterization of the academic research example which encompasses a wide variety of other situations is the following. A risk neutral principal hires a risk averse agent to produce quality which is unobservable by the principal but generates a random stream of revenues. Unobservable effort and observable capital costs are perfect complements in the production of quality. The minimum level of capital cost required to produce a given level of quality is determined by a random production shock which is observed by the agent before choosing effort. The agent then chooses effort and selects the minimum level of cost to induce the level of quality indicated by his effort. Revenues are then determined by quality and a random shock.

In the above model expected capital costs and revenues are increasing in effort and furthermore there is no relationship between the random process which generates revenues and that which generates costs. As a result both can be fruitfully used as signals regarding agent effort, as shown in a general context by Hölmstrom (1979). The purpose of our analysis is thus to explore the manner in which the principal uses these two signals to compensate the agent. In particular we address the issue of whether or not the principal will reward or punish the incurring of capital costs. In the latter instance the agent will have an incentive to overstate the capital costs required to implement his effort. Consequently the principal will be induced to set up a monitoring system to detect bogus capital expense claims reported by the agent. We argue that in this instance these monitoring costs will be sufficently low to merit using capital costs as a signal. Furthermore we assume that the principal offers a contract which specifies a set of linear revenue and capital cost shares. The linearity assumption is restrictive but has the virtue of simplicity. Furthermore Hölmstrom and Milgrom (1987) and Laffont and Tirole (1986, 1987) have shown that in certain cases linearity is optimal.

The paper is organized as follows. In Section I we describe the model and consider the benchmark observable effort case. The unobservable effort case is then discussed in Section II.

I THE MODEL AND OBSERVABLE EFFORT

A risk neutral principal hires a risk averse agent to produce quality q which requires agent effort x and capital costs C as inputs. The two inputs are perfect complements and the minimum level of C required to produce a given level of q is determined by the random variable θ. The production of quality is thus given by

(1) $q = \min\{x,\ C - \theta\}$

The contract offerred by the principal specifies a level of quality or effort and a wage schedule $\omega(\varepsilon,\theta)$. Assuming that the agent observes the production shock and selects the minimum level of capital cost associated with the level of effort or quality implies

(2) $q = x$

(3) $C = x + \theta \equiv C(x,\theta)$

Now assume that revenues are determined by $q = x$ and a random term ε in the following linear fashion

(4) $R = ax + \varepsilon \equiv R(x,\varepsilon)$ where $a > 1$

Agent utility U depends on wealth W which is defined as the wage minus effort costs $e(x)$. Now let subscripts denote partial derivatives then risk aversion and the assumption of convex effort costs imply

(5a) <u>Utility</u> : $U_W > 0$ and $U_{WW} < 0$

(5b) <u>Effort</u> : $e_x > 0$ and $e_{xx} > 0$

Now let $E\{\cdot\}$ or $\bar{\ }$ denote expectation then the objective functions for agent and principal are given by $\bar{A}$ and $\tilde{P}$ respectively as follows

(6a) $\bar{A} \equiv E\{A\} = E\left\{U(W)\right\}$ where $W = \omega(\varepsilon,\theta) - e(x)$

(6b) $\bar{P} \equiv E\{P\} = E\left\{R(x,\varepsilon) - C(x,\theta) - \omega(\varepsilon,\theta)\right\}$

If competition between agents ensures that each agent receives only his reservation utility $\hat{A}$ and if λ denotes a LaGrange multiplier then the first-best problem of the principal is to choose x and $\omega(\varepsilon,\theta)$ to maximize

(7) $\mathcal{L}^{fb}(\cdot) = E\left\{R(x,\varepsilon) - C(x,\theta) - \omega(\varepsilon,\theta)\right\} + \lambda\left[E\left\{U\left(\omega(\varepsilon,\theta) - e(x)\right)\right\} - \hat{A}\right]$

Differentiating (7) with respect w (in piecewise fashion) and x gives

(8a) $\mathcal{L}^{fb}_w = -1 + \lambda U_w = 0$ for all ε and θ

(8b) $\mathcal{L}^{fb}_x = R_x - C_x - \lambda\bar{U}_w e_x = 0$

Substituting (8a) into (8b) we obtain the productive efficiency condition

(8b)' $R_x - C_x - e_x = 0$

II UNOBSERVABLE EFFORT

Now assume that agent effort and quality are both unobservable. Furthermore assume that the contract offerred by the principal specifies the agent's salary S and his linear share of revenues (r) and costs (k) then

(9) $\omega(\varepsilon,\theta) = S + rR(x,\varepsilon) - kC(x,\theta)$

We continue to assume that the agent observes the production shock and selects the minimum level of capital costs for any level of quality. As a result the agent's choice of effort also implies a level of capital cost and is given by substituting (9) into (6a) and then maximizing with respect to x to obtain

(10) $\bar{A}_x \equiv E\left\{U_w\left[rR_x - kC_x - e_x\right]\right\} = 0$

Since R_x, C_x and e_x are non-random then (10) implies

(10)' $rR_x - kC_x - e_x = 0$

Furthermore the solution to (10)' is non-random is given by

(11a) $x = x(r,k)$ where

(11b) $x_r = a/e_{xx} > 0$

(11c) $x_k = -1/e_{xx} < 0$

represent comparative statics and were obtained by differentiating (10)' and then using (3), (4) and (5b). Substituting (9) and (11a) into (7) then yields

$$\mathcal{L}^{sb}(\cdot) = E\left\{[1 - r]R\left(x(r,k),\varepsilon\right) - [1 - k]C\left(x(r,k),\theta\right)\right\} - S + \lambda\left[E\left\{U\left(S + rR\left(x(r,k),\varepsilon\right) - kC\left(x(r,k),\theta\right) - e\left(x(r,k)\right)\right)\right\} - \hat{A}\right] \tag{12}$$

as the principal's second-best problem. Now let terms with(out) bars denote expectation of (non)-random terms and define

(13) $P_x \equiv E\left\{[1 - r]R_x - [1 - k]C_x\right\} = [1 - r]R_x - [1 - k]C_x$

as the principal's marginal benefit of agent effort then maximizing (12) with respect to r,k and S yields

(14a) $\mathcal{L}^{sb}_r = -\bar{R} + P_x x_r + \lambda\left[\overline{U_w R} + \bar{A}_x x_r\right] = 0$

(14b) $\mathcal{L}^{sb}_k = \bar{C} + P_x x_k + \lambda\left[-\overline{U_w C} + \bar{A}_x x_k\right] = 0$

(14c) $\mathcal{L}^{sb}_S = -1 + \lambda\bar{U}_w = 0$

Now set $\bar{A}_x = 0$ by the Envelope Theorem and then substitute (14c) into (14a) and (14b) to obtain

$$\left[-\bar{R} + P_x x_r\right]\bar{U}_w + \overline{U_w R} = 0 \tag*{(15a)}$$

$$\left[\bar{C} + P_x x_k\right]\bar{U}_w - \overline{U_w C} = 0 \tag*{(15b)}$$

Now substitute

$$\overline{U_w R} = \mathrm{cov}(U_w, R) + \bar{U}_w \bar{R} \tag*{(16a)}$$

$$\overline{U_w C} = \mathrm{cov}(U_w, C) + \bar{U}_w \bar{C} \tag*{(16b)}$$

into (15) to obtain

$$\mathrm{cov}(U_w, R) + \bar{U}_w P_x x_r = 0 \tag*{(15a)'}$$

$$-\mathrm{cov}(U_w, C) + \bar{U}_w P_x x_k = 0 \tag*{(15b)'}$$

which yield the following proposition.

PROPOSITION 1 : The optimal risk sharing and productive efficiency conditions associated with the second best unobservable effort case are given by

$$x_r \mathrm{cov}(U_w, C) = -x_k \mathrm{cov}(U_w, R) \qquad \text{[risk sharing]} \tag*{(17)}$$

$$R_x - C_x - e_x = \frac{\mathrm{cov}(U_w, C)}{\bar{U}_w x_k} \qquad \text{[productive efficiency]} \tag*{(18)}$$

Proof : (17) is directly implied by (15)'. To derive (18) we substitute (13) into (15b)' to obtain

$$R_x - C_x - \frac{\mathrm{cov}(U_w, C)}{\bar{U}_w x_k} = rR_x - kC_x \tag*{(19)}$$

which when substituted into (10)' implies (18). Q.E.D.

In order so say something about the signs of r and k we consider a first-order Taylor series expansion around $\{\bar{\varepsilon}, \bar{\theta}\}$ of the marginal utility of wealth evaluated at $x(r,k)$ (see Thomas (1972)). Since $x \equiv x(r,k)$ is non-random then this approximation is given by

$$U_w(x,\varepsilon,\theta) \cong U_w(x,\bar{\varepsilon},\bar{\theta}) + U_{w\varepsilon}(x,\bar{\varepsilon},\bar{\theta})\left[\varepsilon - \bar{\varepsilon}\right] + U_{w\theta}(x,\bar{\varepsilon},\bar{\theta})\left[\theta - \bar{\theta}\right] \tag*{(20)}$$

where

$$U_{w\varepsilon}(x,\bar{\varepsilon},\bar{\theta}) = U_{ww}(x,\bar{\varepsilon},\bar{\theta})r \tag*{(21a)}$$

$$U_{w\theta}(x,\bar{\varepsilon},\bar{\theta}) = -U_{ww}(x,\bar{\varepsilon},\bar{\theta})k \tag*{(21b)}$$

Now substitute (21) into (20) to obtain

$$U_w(x,\varepsilon,\theta) \cong U_w(x,\bar{\varepsilon},\bar{\theta}) + U_{ww}(x,\bar{\varepsilon},\bar{\theta})\left[r[\varepsilon - \bar{\varepsilon}] - k[\theta - \bar{\theta}]\right] \tag*{(20)'}$$

which yields the following proposition. (see Appendix for proof).

PROPOSITION 2 : Let σ_ε and σ_θ denote standard deviations and ρ denote the correlation coefficient between ε and θ. Now define $\rho^* \equiv \sigma_\varepsilon / a\sigma_\theta > 0$. If marginal utility is approximated using a first-order Taylor series expansion then the following properties arise

i) if $\rho > \rho^* < 1$ then $r > 0$ and $k > 0$

ii) if $\rho > 1/\rho^* < 1$ then $r < 0$ and $k < 0$

iii) if $\rho < \min\{\rho^*, 1/\rho^*\}$ then $r > 0$ and $k < 0$

iv) if $\rho^2 = 1$ then the <u>first best</u> is attained using the following scheme

a) if $\rho = 1$ then $r \cong \dfrac{R_x - C_x}{R_x - \left[\dfrac{\sigma_\varepsilon}{\sigma_\theta}\right]C_x}$ and $k \cong \dfrac{R_x - C_x}{\left[\dfrac{\sigma_\theta}{\sigma_\varepsilon}\right]R_x - C_x}$

b) if $\rho = -1$ then $r \cong \dfrac{R_x - C_x}{R_x + \left[\dfrac{\sigma_\varepsilon}{\sigma_\theta}\right]C_x}$ and $k \cong \dfrac{R_x - C_x}{-\left[\dfrac{\sigma_\theta}{\sigma_\varepsilon}\right]R_x - C_x}$

v) if $\rho^2 \neq 1$ then effort is underprovided.

Proposition 2 states that when the revenue and cost signals are not sufficiently positively correlated (parts (iiii) and (iv) b)) then there is relatively less risk and thus the principal is mainly with providing incentives. He does so by rewarding the agent for incurring costs ($k < 0$) as well as earning revenues ($r > 0$). On the other hand when the cost and revenue signals are too positively correlated (parts (i), (ii) and (iv) a)) then the income stream becomes more risky thereby inducing the principal to become more concerned about minimizing agent risk. As a result the principal rewards revenues or costs but not both. In particular revenues (costs) are rewarded and costs (revenues) are punished when revenues (costs) have relatively low variance. Furthermore effort is underprovided because the principal trades-off reduced productive efficiency for risk-sharing gains.

APPENDIX : PROOF OF PROPOSITION 2

1) Taking an expectation of (20)' we obtain the following expression for expected marginal utility of wealth evaluated at x

$$\text{(A1)}\quad \bar{U}_w(x,\varepsilon,\theta) \cong U_w(x,\bar{\varepsilon},\bar{\theta})$$

which when combined with (20)' yields

$$\text{(A2)}\quad U_w(x,\varepsilon,\theta) - \bar{U}_w(x,\varepsilon,\theta) \cong U_{ww}(x,\bar{\varepsilon},\bar{\theta})\Big[r\big[\varepsilon - \bar{\varepsilon}\big] - k\big[\theta - \bar{\theta}\big]\Big]$$

Using (3) and (4) we obtain

$$\text{(A3a)}\quad R(x,\varepsilon) - \bar{R}(x,\varepsilon) = \big[\varepsilon - \bar{\varepsilon}\big]$$

$$\text{(A3b)}\quad C(x,\theta) - \bar{C}(x,\theta) = \big[\theta - \bar{\theta}\big]$$

Now (A3a) and (A2) result in

$$\begin{aligned}\text{(A4)}\quad \operatorname{cov}(U_w,R) &\equiv E\Big\{\Big[U_w(x,\varepsilon,\theta) - \bar{U}_w(x,\varepsilon,\theta)\Big]\Big[R(x,\varepsilon) - \bar{R}(x,\varepsilon)\Big]\Big\} \\ &\cong E\Big\{U_{ww}(x,\bar{\varepsilon},\bar{\theta})\Big[r\big[\varepsilon - \bar{\varepsilon}\big]^2 - k\big[\varepsilon - \bar{\varepsilon}\big]\big[\theta - \bar{\theta}\big]\Big]\Big\} \\ &\cong U_{ww}(x,\bar{\varepsilon},\bar{\theta})\Big[r\sigma_{\varepsilon}^2 - k\rho\sigma_{\varepsilon}\sigma_{\theta}\Big]\end{aligned}$$

Similarly (A2) and (A3b) derive

$$\text{(A5)}\quad \operatorname{cov}(U_w,C) \cong U_{ww}(x,\bar{\varepsilon},\bar{\theta})\Big[r\rho\sigma_{\varepsilon}\sigma_{\theta} - k\sigma_{\theta}^2\Big]$$

Substituting (A4), (A5), (11b) and (11c) into (17) we obtain the following relationship between r and k which can be written in one of two ways

$$\text{(A6a)}\quad r \cong k \cdot \left[\frac{a\sigma_\theta^2 - \rho\sigma_\varepsilon\sigma_\theta}{a\rho\sigma_\varepsilon\sigma_\theta - \sigma_\varepsilon^2}\right]$$

$$\text{(A6b)}\quad r \cong k \cdot \frac{-1}{a} \cdot \left[\frac{\rho - \dfrac{1}{\rho^*}}{\rho - \rho^*}\right] \quad \text{where } \rho^* = \frac{\sigma_\varepsilon}{a\sigma_\theta}$$

Substituting (A6a) into $rR_x - kC_x$ and $\operatorname{cov}(U_w, C)$ yields

$$\text{(A7)}\quad rR_x - kC_x \cong k \cdot \left[\frac{\left[a\sigma_\theta - \sigma_\varepsilon\right]^2 + 2a\sigma_\varepsilon\sigma_\theta\left[1 - \rho\right]}{a\rho\sigma_\varepsilon\sigma_\theta - \sigma_\varepsilon^2}\right] \quad \text{and}$$

$$\text{(A8)}\quad \operatorname{cov}(U_w, C) \cong k \cdot \left[\frac{\sigma_\varepsilon^2\sigma_\theta^2\left[1 - \rho^2\right]\; U_{ww}(x, \bar{\varepsilon}, \bar{\theta})}{a\rho\sigma_\varepsilon\sigma_\theta - \sigma_\varepsilon^2}\right]$$

Now let $U_{ww}(x, \bar{\varepsilon}, \bar{\theta}) = U_{ww}(\cdot)$ and then substitute (A7), (A8) and $\rho^* = \sigma_\varepsilon / a\sigma_\theta$ into (19) to obtain

$$\text{(A9)}\quad k \cong \frac{\overset{(+)}{\bar{U}_w}\overset{(+)}{\left[R_x - C_x\right]}\overset{(+)}{a\sigma_\varepsilon\sigma_\theta}\left[\rho - \rho^*\right]}{\left[\underset{(+)}{\left[a\sigma_\theta - \sigma_\varepsilon\right]^2} + \underset{(+)}{2a\sigma_\varepsilon\sigma_\theta}\underset{(+)}{\left[1 - \rho\right]}\right]\underset{(+)}{\bar{U}_w} + \underset{(+)}{\sigma_\varepsilon^2\sigma_\theta^2}\underset{(-)}{\left[\rho^2 - 1\right]}\underset{(-)}{U_{ww}(\cdot)}\underset{(+)}{e_{xx}}}$$

Substituting (A6b) into (A9) gives

$$\text{(A10)}\quad r \cong \frac{\overset{(-)}{-\bar{U}_w}\overset{(+)}{\left[R_x - C_x\right]}\overset{(+)}{\sigma_\varepsilon\sigma_\theta}\left[\rho - 1/\rho^*\right]}{\left[\underset{(+)}{\left[a\sigma_\theta - \sigma_\varepsilon\right]^2} + \underset{(+)}{2a\sigma_\varepsilon\sigma_\theta}\underset{(+)}{\left[1 - \rho\right]}\right]\underset{(+)}{\bar{U}_w} + \underset{(+)}{\sigma_\varepsilon^2\sigma_\theta^2}\underset{(+)}{\left[\rho^2 - 1\right]}\underset{(-)}{U_{ww}(\cdot)}\underset{(+)}{e_{xx}}}$$

<u>i)</u> If $\rho > \rho^* < 1$ then $k < 0$ from (A9). Furthermore since $\rho^* < 1$ then $1/\rho^* > 1$ and thus $\rho < 1/\rho^*$ since $-1 \leq \rho \leq 1$. Since $\rho < 1/\rho^*$ then from (A10) we obtain $r > 0$ as required.

<u>ii)</u> If $\rho > 1/\rho^* < 1$ then $r < 0$ from (A10). Furthermore since $1/\rho^* < 1$ then $\rho^* > 1$ and thus $\rho < \rho^*$ since $-1 \leq \rho \leq 1$. Since $\rho < \rho^*$ then from (A9) we obtain $k < 0$ as required.

<u>iii)</u> $\rho < 1/\rho^*$ and (A10) imply $r > 0$. $\rho < \rho^*$ and (A9) imply $k < 0$.

<u>iv)</u> In order to show that the agent receives a riskless return when $\rho^2 = 1$ we examine the variance of the marginal utility of income. Taking an expectation of the square of (A2) yields

$$\text{(A11a)}\quad \operatorname{var}(U_w) \equiv E\left\{\left[U_w(x, \varepsilon, \theta) - \bar{U}_w(x, \varepsilon, \theta)\right]^2\right\}$$

$$\text{(A11b)}\quad \cong E\left\{\left[U_{ww}(x, \bar{\varepsilon}, \bar{\theta})\right]^2\left[r\left[\varepsilon - \bar{\varepsilon}\right] - k\left[\theta - \bar{\theta}\right]\right]^2\right\}$$

$$\text{(A11c)}\quad \cong \left[U_{ww}(x, \bar{\varepsilon}, \bar{\theta})\right]^2\left[\left[r\sigma_\varepsilon\right]^2 - 2rk\rho\sigma_\varepsilon\sigma_\theta + \left[k\sigma_\theta\right]^2\right]$$

Substituting $\rho = 1$ and $\rho = -1$ into (A11c) yields

$$\text{(A12a)}\quad \operatorname{var}(U_w) \cong \left[U_{ww}(x, \bar{\varepsilon}, \bar{\theta})\right]^2\left[r\sigma_\varepsilon - k\sigma_\theta\right]^2 \text{ if } \rho = 1$$

$$\text{(A12b)}\quad \operatorname{var}(U_w) \cong \left[U_{ww}(x, \bar{\varepsilon}, \bar{\theta})\right]^2\left[r\sigma_\varepsilon + k\sigma_\theta\right]^2 \text{ if } \rho = -1$$

Substituting $\rho = 1$ and $\rho = -1$ into (A6a) gives

(A13a) $r \cong k\sigma_\theta/\sigma_\varepsilon$ if $\rho = 1$

(A13b) $r \cong -k\sigma_\theta/\sigma_\varepsilon$ if $\rho = -1$

Substituting (A13) into (A12) we obtain that $\operatorname{var}(U_w) = 0$ when $\rho^2 = 1$

which implies that the agent bears none of the risk. Furthermore by substituting $\rho^2 = 1$ into (A8) we obtain that $\mathrm{cov}(U_w, C) \cong 0$ which implies that (18) and (8b)' coincide and thus that the first-best level of effort is provided. The incentive scheme which gives rise to this first-best outcome is obtained by substituting $\mathrm{cov}(U_w, C) \cong 0$ into (19) to obtain

$$\text{(A14)}\quad k \cong \frac{R_x - C_x}{[r/k]R_x - C_x} \quad \text{and/or} \quad r \cong \frac{R_x - C_x}{R_x - [k/r]C_x}$$

Substituting (A13) into (A14) yields the result.

v) Now substitute (A9) into (A8) and then divide by $\bar{U}_w x_k$ and use $\rho^* = \sigma_\varepsilon / a\sigma_\theta$ to obtain

$$\text{(A15)}\quad \frac{\mathrm{cov}(U_w, C)}{\tilde{U}_w x_k} \cong \frac{\overset{(+)}{\left[R_x - C_x\right]}\,\overset{(+)}{\sigma_\varepsilon^2\sigma_\theta^2}\,\overset{(-)}{\left[\rho^2 - 1\right]}\,\overset{(-)}{U_{ww}(\cdot)}\,\overset{(+)}{e_{xx}}}{\left[\underset{(+)}{\left[a\sigma_\theta - \sigma_\varepsilon\right]^2} + 2a\underset{(+)}{\sigma_\varepsilon\sigma_\theta}\underset{(+)}{[1-\rho]}\right]\underset{(+)}{\tilde{U}_w} + \underset{(+)}{\sigma_\varepsilon^2\sigma_\theta^2}\underset{(-)}{\left[\rho^2 - 1\right]}\underset{(-)}{U_{ww}(\cdot)}\underset{(+)}{e_{xx}}} > 0$$

which implies underprovision given (18), (8b)' and (5b). Q.E.D.

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