Motivating Innovation

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Abstract

Motivating innovation is an important concern in many incentive problems. For example, managers often claim that it is difficult to motivate their employees to devise innovative ways of doing things. The difficulty arises because innovation is the result of the exploration of untested approaches that are likely to fail, and failure is usually associated with low wages and termination. This paper shows that incentive schemes that motivate exploration are fundamentally different from standard pay-for-performance incentive schemes used to motivate effort. The optimal compensation scheme that motivates exploration exhibits substantial tolerance (or even reward) for early failure and reward for long-term success. Moreover, even though the principal can terminate the agent, inefficient continuation may be optimal to induce exploration since the threat of termination may prevent the agent from exploring new untested approaches. Finally, commitment to a long-term compensation plan and timely feedback on performance are essential ingredients to induce exploration. The institution of tenure, debtor-friendly bankruptcy laws, and golden parachutes are examples of schemes that protect the agent when failure occurs and thereby encourage exploration.

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Results? Why, man, I have gotten lots of results! I know several thousands of things that won't work. *Thomas Edison*

1 Introduction

Innovation is vital for the long-term growth and performance of organizations. Top executives in business organizations are aware of that. In a recent survey,[1] approximately 78 percent of the 540 CEOs interviewed said that "stimulating innovation, creativity, and enabling entrepreneurship" is a top priority of their organizations. Motivating innovation remains, however, a challenge for most organizations. Innovation results from the exploration of new untested approaches that are likely to fail. Therefore, standard pay-for-performance schemes that punish failures with low wages and termination may have adverse effects on innovation.

This paper shows that incentive schemes that motivate innovation are fundamentally different from standard pay-for-performance incentive schemes used to induce effort. The optimal compensation scheme that motivates innovation exhibits substantial tolerance (or even reward) for early failure and reward for long–term success. Moreover, even though the principal can terminate the agent, excessive continuation may be optimal to motivate innovation since the threat of termination may prevent the agent from exploring new untested approaches. Finally, commitment to a long–term compensation plan and timely feedback on performance are also essential ingredients to motivate innovation.

Some commonly used incentive schemes protect or even reward the agent when failure occurs. For example, innovative corporations such as 3M and IBM are known for having corporate cultures that tolerate failure. Research departments in business and academic organizations grant researchers tenure, securing them a job even if their subsequent productivity is low. Executive compensation packages include golden parachutes and option repricing, rewarding executives after poor performance. An entrenched manager may keep his job even if it is ex post efficient for the firm to fire him. Debtor-friendly bankruptcy laws allow entrepreneurs a fresh start after failure. These incentive schemes are often criticized because, by protecting or rewarding the agent after poor performance, they undermine the incentives for the agent to exert effort. This paper shows that these incentive schemes may arise as part of an optimal contract that motivates exploration. Restricting their use may thus have adverse effects on innovation.

To model the process of innovation, I use a class of Bayesian decision models known as bandit problems.[2] In bandit problems, the agent is uncertain about the true distribution of

[1] "CEO Challenge 2004: Perspectives and Analysis," The Conference Board, Report 1353.

[2] Berry and Fristedt (1985) provides an introduction to the statistical literature on bandit problems. Bergemann and Valimaki (2006) survey the applications of bandit problems to economics.

payoffs of the available actions. Innovation in this setting is the discovery, through experimentation and learning, of actions that are superior to previously known actions. I focus on the central concern that arises in bandit problems: the tension between the exploration of new untested actions and the exploitation of well known actions. Exploration of new untested actions reveals information about potentially superior actions, but is also likely to waste time with inferior actions. Exploitation of well known actions ensures reasonable payoffs, but may prevent the discovery of superior actions.

To study the incentives for exploration and exploitation, I embed a bandit problem into a principal principal-agent framework. The model has two periods and two possible outcomes in each period (success or failure). In each period the agent can choose between shirking, exploiting a well-known approach, or exploring a novel approach, which has an unknown probability of success.

The model has two important special cases. On one hand, if exploration and exploitation are costless to the agent, there is no conflict of interest between the principal and the agent. The model then reduces to the two-armed bandit problem that captures the tension between exploration and exploitation. On the other hand, if exploration is extremely costly to the agent, the agent chooses between exploitation or shirking. The model then reduces to a standard principal-agent model where the principal must motivate the agent to exert effort. Therefore, the model developed here incorporates the tension between exploration and exploitation present in bandit problems, as well as the tension between working and shirking present in standard principal-agent models.

The optimal contracts that motivate exploitation and exploration are fundamentally different from each other. Since exploitation is just the repetition of well known actions, the optimal contract that motivates exploitation is similar to standard pay-for-performance contracts used to motivate repeated effort, such as the contracts obtained in Holmstrom and Milgrom (1987). On the other hand, since with exploration the agent is likely to waste time with inferior actions, the optimal contract that motivates exploration exhibits substantial tolerance (or even reward) for early failures. Moreover, since exploration reveals information that is useful for future decisions, the optimal contract that motivates exploration rewards long-term success. Under the optimal exploration contract, an agent that obtains an early failure followed by a success earns more than an agent that obtains an early success followed by a failure. Even an agent that fails twice may earn more than an agent that obtains a success followed by a failure.

The paper also studies the distortions relative to the first-best produced by agency problems. It shows that the principal is biased towards exploration if only the shirking constraints are binding when implementing exploration. On the other hand, the principal is biased against exploration if the exploitation constraint is binding when implementing exploration.

The ability of the principal to commit to a long-term contract has different effects on the incentives for exploitation and exploration. Since the optimal contract that motivates exploitation relies on short-term incentives, the ability to commit to a long-term contract is irrelevant to motivate exploitation. This result is related to the result of Fudenberg, Holmstrom, and Milgrom (1990). In contrast, the optimal contract that motivates exploration relies on long-term incentives. Not only are short-term contracts strictly dominated by long-term contracts, but exploration may not even be implementable with a sequence of short-term contracts. The ability to commit to a long-term contract is thus essential to motivate exploration.

The paper also studies the effects of termination after poor performance on the incentives for exploration and exploitation. Since the threat of termination helps to prevent the agent from shirking or exploring new actions, termination facilitates the provision of incentives for exploitation. Excessive termination may thus be optimal to motivate exploitation. This result is related to the results of Stiglitz and Weiss (1983) in a model of repeated effort. In contrast, the effects of termination on the incentives for exploration are ambiguous. On one hand, the threat of termination prevents the agent from shirking. On the other hand, the threat of termination encourages the agent to exploit well-known actions. Depending on which of these two effects is more important, termination may either facilitate or hinder the provision of incentives for exploration. Either excessive termination or continuation may thus be optimal to motivate exploration.

The paper studies the role of feedback on performance when the principal is better able than the agent to evaluate performance. If the principal does not provide feedback on performance to the agent, then the agent cannot adjust his action according to performance. There are thus fewer deviations that the agent can attempt. Therefore, it is cheaper to motivate exploitation if the principal does not provide feedback on performance to the agent, as in Lizzeri, Meyer, and Persico (2002) and Fuchs (2007). In contrast, since exploration requires the agent to adjust his action after poor performance, feedback on performance is essential to motivate exploration.

Related Literature Other papers have studied the incentives for innovation from an organizational perspective. Holmstrom (1989) proposes an alternative explanation for why incentives schemes that motivate innovation must exhibit tolerance for failures. He argues that performance measures for innovative activities are noisier, and therefore to motivate innovation the principal should rely on compensation schemes that are less sensitive to performance. In the same vein, Aghion and Tirole (1994) argue that the outcomes of innovation activities are unpredictable and, therefore, hard to contract ex ante. In an incomplete contract framework, they derive the optimal allocation of control rights that motivates innovation. These two papers focus on measurability and contractability aspects of the innovation activity. In contrast, the present paper models the innovation process explicitly and focuses on the central trade-off that arises in innovation activities, the trade-off between exploration and exploitation.

The model of the innovation process adopted here follows a long tradition in the study of innovation. Schumpeter (1934) argues that innovation results from the experimentation with "new combinations" of existing resources. Arrow (1969) associates innovation with the production of knowledge and proposes the use of Bayesian decision models to study innovation. Bandit problems are Bayesian decision models that allow for knowledge acquisition through experimentation. Weitzman (1979) applies a simple bandit problem to study the innovation process. March (1991) uses the terms exploration and exploitation to describe the fundamental tension that arises in learning through experimentation. The literature in industrial organization, including Roberts and Weitzman (1981), Jensen (1981), Battacharya, Chatterjee, and Samuelson (1986), and Moscarini and Smith (2001), has relied extensively on bandit problem and related models of learning through experimentation to study the innovation process. Also, recent papers on growth theory, such as Jovanovic and Rob (1990), Jovanovic and Nyarko (1996) and Aghion (2002), develop quite detailed models of innovation as the result of learning from the exploration of new technologies. Bolton and Harris (1999) study strategic experimentation in a setting where multiple players face the same experimentation problem. Each agent learns from the experimentation of the other players. Since information is a public good, there is free riding and under-experimentation in equilibrium. In contrast to these papers, which take the payoffs of the players as given, I study optimal compensation schemes that motivate exploration and exploitation.

Other papers have studied principal-agent models in which the choice of the agent is not limited to the level of effort. Lambert (1986) analyzes the provision of incentives when the agent selects among risky projects. Holmstrom and Milgrom (1991) develop a multi-task principal-agent model in which the agent allocates effort among multiple tasks and the principal observes a performance measure for each of these tasks. Dewatripont and Maskin (1995) and Von Thadden (1995) analyze incentives for the agent to select between short-term and long-term investments. In these models, the agent does not learn about the distribution of payoffs. Moreover, the agent takes an action in the first period and cannot change it later on. Therefore, these models do not incorporate experimentation, learning, and adaptation, important features of innovation.

To study the financing of innovation, Bergemann and Hege (2005) develop a principal-agent model in which there is learning about the quality of the project. The tension between exploration and exploitation does not arise in their model though, as the agent can only choose one type of project. Moreover, their paper only considers implementation with a sequence of short-term contracts.[3] Also related are Hellmann (2007) and Hellmann and

[3]Two other recent papers, Lewis and Ottaviani (2008) and Gerardi and Maestri (2008), study incen-

Thiele (2008), who study incentives for innovation using a multi-task principal-agent model.

Several papers provide evidence supporting the theoretical results derived here. For example, Acharya and Subramanian (2009) analyze the effect of bankruptcy laws on entrepreneurship using cross-sectional and time series data of several countries. They find that debtor friendly bankruptcy laws lead to more innovation. Acharya, Baghai-Wadji, and Subramanian (2009) study the effect of stringent labor laws that restrict the dismissal of employees on innovation. They find that stringent labor laws encourage firm-level innovation. Lerner and Wulf (2007) show that long-term incentives to the heads of research and development departments are associated with more heavily cited patents, while short-term incentives are unrelated to measures of innovation. In a laboratory experiment, Ederer and Manso (2009) show that compensation schemes that tolerate early failure and reward long-term success encourage innovation.

The paper is organized as follows. Section 2 discusses the tension between exploration and exploitaiton in a single-agent decision problem. Section 3 introduces the tension between exploration and exploitation into a principal-agent model. Section 4 studies incentives for exploration and exploitation and the distortions generated by the agency conflict. Section 5 studies implementation without commitment. Section 6 studies the optimal termination policy of the principal. Section 7 studies the provision of feedback. Section 8 discusses applications of the model. Section 9 contains additional discussion and Section 10 concludes. All proofs are in the Appendix.

2 The Single-Agent Decision Problem

In this section, I review the classical two-armed bandit problem with one known arm. This model illustrates the tension between exploration and exploitation in a single-agent decision problem.

The agent lives for two periods. In each period, the agent takes an action $i \in \mathcal{I}$, producing output S ("success") with probability p_i or output F ("failure") with probability $1 - p_i$. The probability p_i of success when the agent takes action $i \in \mathcal{I}$ may be unknown. To obtain information about p_i, the agent needs to engage in experimentation. I let $E[p_i]$ denote the unconditional expectation of p_i, $E[p_i|S, j]$ denote the conditional expectation of p_i given a success on action j, and $E[p_i|F, j]$ denote the conditional expectation of p_i given a failure on action j. When the agent takes action $i \in \mathcal{I}$, he only learns about the probability p_i, so that

$$E[p_j] = E[p_j|S, i] = E[p_j|F, i] \quad \text{for} \quad j \neq i.$$

tive problems with learning about some fundamental parameter of the model. Both papers are closer to Bergemann and Hege (2005) in that there is no tension between exploration and exploitation.

The central concern that arises when the agent learns through experimentation is the tension between exploration of new actions and exploitation of well known actions. To focus on the tension between exploration and exploitation, I assume that in each period the agent chooses between two actions. Action 1, the conventional work method, has a known probability p_1 of success, such that

$$p_1 = E[p_1] = E[p_1|S, 1] = E[p_1|F, 1].$$

Action 2, the new work method, has an unknown probability p_2 of success such that

$$E[p_2|F, 2] < E[p_2] < E[p_2|S, 2].$$

I assume that the new work method is of exploratory nature. This means that when the agent experiments with the new work method, he is initially not as likely to succeed as when he conforms to the conventional work method. However, if the agent observes a success with the new work method, then the agent updates his beliefs about the probability p_2 of success with the new work method, so that the new work method becomes perceived as better than the conventional work method. This is captured by:

$$E[p_2] < p_1 < E[p_2|S, 2]. \tag{1}$$

The agent is risk-neutral and has a discount factor normalized to one. The agent thus chooses an action plan $\langle {}_i{}^j_k \rangle$ to maximize his total expected payoff

$$\begin{aligned} R(\langle {}_i{}^j_k \rangle) = \{E[p_i]S + (1 - E[p_i])F\} & \\ + E[p_i]\{E[p_j|S, i]S + (1 - E[p_j|S, i])F\} & \\ + (1 - E[p_i])\{E[p_k|F, i]S + (1 - E[p_k|F, i])F\}, & \quad (2) \end{aligned}$$

where $i \in \mathcal{I}$ is the first-period action, $j \in \mathcal{I}$ is the second-period action in case of success in the first period, and $k \in \mathcal{I}$ is the second-period action in case of failure in the first period.

Two action plans need to be considered. Action plan $\langle {}_1{}^1_1 \rangle$, which I call exploitation, is just the repetition of the conventional work method. Action plan $\langle {}_2{}^2_1 \rangle$, which I call exploration, is to initially try the new work method, stick to the new work method in case of success in the first period, and revert to the conventional work method in case of failure in the first period. The total payoff $R(\langle {}_2{}^2_1 \rangle)$ from exploration is higher than the total payoff $R(\langle {}_1{}^1_1 \rangle)$ from exploitation if and only if

$$E[p_2] \geq p_1 - \frac{p_1(E[p_2|S, 2] - p_1)}{1 + (E[p_2|S, 2] - p_1)}. \tag{3}$$

If the agent tries the new work method, he obtains information about p_2. This information is useful for the agent's decision in the second period, since the agent can switch to the conventional work method in case he learns that the new work method is not worth pursuing. The agent may thus be willing to try the new work method even though the initial expected probability $E[p_2]$ of success with the new work method is lower than the probability p_1 of success with the conventional work method. The second term on the right-hand side of equation (3) represents the premium in terms of first-period payoff that the agent is willing to pay to obtain information about p_2.

The agent is willing to sacrifice more in the first period if he lives for multiple periods. With multiple periods, the benefits of experimenting with the new work method are higher, since the agent can use the information he learns from experimentation for a longer period of time. The same is true if the problem is to maximize the output of a team. In a team, the optimal action plan involves more sacrificing of first period output for at least one of the agents. In case the agent discovers that the new work method is better than the conventional work method, the whole team benefits from his discovery.

3 The Principal-Agent Problem

In this section, I introduce incentive problems into the classical two-armed bandit problem with one known arm reviewed in the previous section.

The principal hires an agent to perform the task described in the previous section. The principal does not observe the actions taken by the agent. In each period, the agent incurs private costs $c_1 \geq 0$ if he takes action 1, the conventional work method, private costs $c_2 \geq 0$ if he takes action 2, the new work method, but can avoid these private costs by taking action 0, shirking. Shirking has a lower probability of success than either of the two work methods, so that

$$p_0 < E[p_i] \quad \text{for} \quad i = 1, 2. \tag{4}$$

Before the agent starts working, the principal offers the agent a contract $\vec{w} = \{w_F, w_S, w_{SF}, w_{SS}, w_{FF}, w_{FS}\}$ that specifies the agent's wages contingent on future performance. The agent has limited liability, meaning that his wages cannot be negative.

Both the principal and the agent are risk-neutral and have a discount factor of 1. When the principal offers the agent a contract $\vec{w}$ and the agent takes action plan $\langle i\, {}^{j}_{k} \rangle$, the total expected payments from the principal to the agent are given by

$$\begin{aligned} W(\vec{w}, \langle i\, {}^{j}_{k} \rangle) = \{E[p_i]w_S + (1 - E[p_i])w_F\} \\ + E[p_i]\{E[p_j|S,i]w_{SS} + (1 - E[p_j|S,i])w_{SF}\} \\ + (1 - E[p_i])\{E[p_k|F,i]w_{FS} + (1 - E[p_k|F,i])w_{FF}\}. \end{aligned}$$

When the agent takes action plan $\langle i\, {}^{j}_{k} \rangle$, the total expected costs incurred by the agent are given by

$$C(\langle i\, {}^{j}_{k} \rangle) = c_i + E[p_i]c_j + (1 - E[p_i])c_k.$$

I say that $\vec{w}$ is an optimal contract that implements action plan $\langle i\,{}^{j}_{k}\rangle$ if it minimizes the total expected payments from the principal to the agent,

$$W(\vec{w}, \langle i\,{}^{j}_{k}\rangle)$$

subject to to the incentive compatibility constraints,[4]

$$W(\vec{w}, \langle i\,{}^{j}_{k}\rangle) - C(\langle i\,{}^{j}_{k}\rangle) \geq W(\vec{w}, \langle l\,{}^{m}_{n}\rangle) - C(\langle l\,{}^{m}_{n}\rangle). \qquad (\mathrm{IC}_{\langle l\,{}^{m}_{n}\rangle})$$

This is a linear program with 6 unknowns and 27 constraints. When there is more than one contract that solves this program, I restrict attention to the contract that pays the agent earlier.[5]

The principal's expected profit $\Pi(\langle i\,{}^{j}_{k}\rangle)$ from implementing action plan $\langle i\,{}^{j}_{k}\rangle$ is given by

$$\Pi(\langle i\,{}^{j}_{k}\rangle) = R(\langle i\,{}^{j}_{k}\rangle) - W(\vec{w}(\langle i\,{}^{j}_{k}\rangle), \langle i\,{}^{j}_{k}\rangle). \qquad (5)$$

where $R(\langle i\,{}^{j}_{k}\rangle)$ is the principal's total expected revenue when the agent uses action plan $\langle i\,{}^{j}_{k}\rangle$, and $\vec{w}(\langle i\,{}^{j}_{k}\rangle)$ is the optimal contract that implements action plan $\langle i\,{}^{j}_{k}\rangle$. The principal thus chooses the action plan $\langle i\,{}^{j}_{k}\rangle$ that maximizes $\Pi(\langle i\,{}^{j}_{k}\rangle)$.

Both the classical two-armed bandit problem and the standard work-shirk principal-agent model are special cases of this model. On one hand, when $c_1 = c_2 = 0$, there is no conflict of interest between the principal and the agent. Therefore, the principal does not need to provide incentives to the agent, and the principal just solves the two-armed bandit problem described in Section 2. On the other hand, when $c_2 = \infty$, it is too costly for the agent to employ the new work method. The agent either shirks or employs the conventional work method. The principal's problem is thus just to prevent the agent from shirking, as in standard principal-agent models.

4 Incentives for Exploration and Exploitation

In this section I study the optimal contracts that implement exploration and exploitation respectively. I also study the distortions relative to the first best produced by agency costs.

The relative costs c_2/c_1 between the new and the conventional work methods will be important in determining which incentive compatibility constraints are binding, and consequently the form of the optimal contract. When c_2/c_1 is high, the agent is more inclined to

[4]For simplicity, I assume that the agent has zero reservation utility. The participation constraints is thus not binding, since the agent has limited liability.

[5]The other contracts that solve the above program are similar to the contract analyzed here except that the principal acts as a bank, keeping the wages of the agent to be paid later without obtaining any additional benefits from this. The contract analyzed here is also the contract that arises if the agent is slightly more impatient than the principal. Previous papers in the literature, such as Biais, Mariotti, Plantin, and Rochet (2007) and DeMarzo and Sannikov (2006) have assumed that the agent is more impatient than the principal.

conform to the conventional work method than to experiment with the new work method. This could be due to the extra effort incurred by the agent when searching and implementing a new work method. When c_2/c_1 is low, the agent is more inclined to experiment with the new work method than to conform to the conventional work method. This could be due to private benefits of learning a new work method. For clarity of exposition, I will restrict attention to

$$c_2/c_1 \geq (E[p_2] - p_0)/(p_1 - p_0). \tag{6}$$

The right-hand side of equation (6) is lower than 1. Restricting attention to (6) thus rules out situations in which the cost of employing the new work method is much lower than the cost of employing the conventional work method. Similar results hold without this restriction. However, the analysis is more complicated and does not add new insights.

4.1 Incentives for Exploitation

Proposition 1 derives the optimal contract that implements exploitation. Recalling from Section 2 exploitation is given by the action plan $\langle {}_1 {}^1_1 \rangle$. The following definitions are useful in stating Proposition 1:

$$\alpha_1 = \frac{c_1}{p_1 - p_0}$$

$$\beta_1 = \frac{(E[p_2] - p_0) + E[p_2](E[p_2|S,2] - p_0)}{(p_1 - p_0) + E[p_2](p_1 - p_0)}$$

Proposition 1 *The optimal contract $\vec{w}_1$ that implements exploitation is such that*

$$w_F = w_{SF} = w_{FF} = 0,$$

$$w_{SS} = w_{FS} = \alpha_1,$$

$$w_S = \alpha_1 + \frac{c_1(1 + E[p_2])}{(p_1 - E[p_2])} \left(\beta_1 - \frac{c_2}{c_1} \right)^+,$$

where $(x)^+ = \max(x, 0)$.

The formal proofs of all the propositions are in the Appendix. Here is the main intuition behind Proposition 1. To implement exploitation, the principal must prevent the agent from shirking and from exploring. If c_2 is high relative to c_1, only shirking constraints are binding, and thus the optimal contract that implements exploitation is similar to the optimal contract used to induce the agent to exert effort in a standard word-shirk principal-agent model. If c_2 is low relative to c_1, the exploration constraint is binding. To prevent exploration, the principal must pay the agent an extra premium in case of success in the first period. This extra premium is decreasing in c_2/c_1, since as c_2/c_1 increases the agent

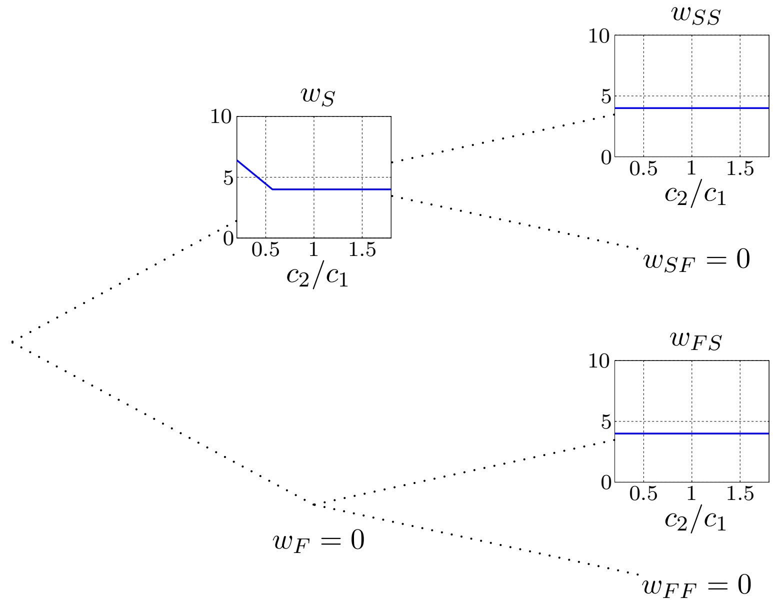

Figure 1: The optimal contract that implements exploitation under the base case parameters.

becomes less inclined to explore. Figure 1 shows the optimal contract $\vec{w}_1$ that implements exploitation for different values of c_2/c_1 under the base case parameters.[6]

4.2 Incentives for Exploration

Proposition 2 derives the optimal contract that implements exploration. Recalling from Section 2, exploration is given by action plan $\langle 2\,{}^2_1 \rangle$. The form of the optimal contract that implements exploration will depend on whether exploration is moderate or radical.

Definition 1 *Exploration is* radical *if*

$$\frac{1-E[p_2]}{1-p_1} \geq \frac{E[p_2]E[p_2|S,2]}{p_1^2},$$

and moderate *otherwise.*

Exploration is radical if the likelihood ratio between exploration and exploitation of a failure in the first period is greater than the likelihood ratio between exploration and exploitation of two consecutive successes. I call this exploration radical because it has a high expected

[6]The base case parameters used in all the figures are $p_0 = 0.25$, $E[p_2] = 0.3$, $p_1 = 0.5$, $E[p_2|S,2] = 0.7$, and $c_1 = 1$. From Bayes' rule, $E[p_2|F,2] = 0.129$. Each of the graphs in the figure corresponds to a wage paid to the agent in a particular contingency for different values of c_2/c_1. When a node has no graphs, it is because the wage paid to the agent in that contingency is zero.

probability of failure in the first period relative to the probability of failure of the conventional action.

The following definitions will also be useful in stating Proposition 2:

$$\alpha_2 = \max_{\tilde{\jmath}\in\{0,1\}} \frac{(1+E[p_2])c_2 - p_0 c_{\tilde{\jmath}}}{E[p_2]E[p_2|S,2] - p_0 E[p_{\tilde{\jmath}}]} + \frac{(E[p_2]-p_0)p_0\alpha_1}{E[p_2]E[p_2|S,2] - p_0 E[p_{\tilde{\jmath}}]}.$$

$$\beta_2 = \frac{(E[p_2]E[p_2|S,2] - p_0 p_1) + E[p_2](p_1 E[p_2|S,2] - p_0 p_1)}{(p_1^2 - p_0 p_1) + E[p_2](p_1^2 - p_0 p_1)}$$

Proposition 2 *The optimal contract $\vec{w}_2$ that implements exploration is such that*

$$w_{FS} = \alpha_1, \quad \textit{and} \quad w_S = w_{SF} = w_{FF} = 0.$$

If exploration is moderate, then $w_F = 0$, and

$$w_{SS} = \alpha_2 + \frac{p_1 - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1^2} \left(\frac{c_2}{c_1} - \beta_2\right)^+.$$

If exploration is radical, then

$$w_F = \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_2\right)^+,$$

and

$$w_{SS} = \alpha_2 + \frac{E[p_2] - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_2\right)^+.$$

To implement exploration, the principal must prevent the agent from shirking or exploiting. The principal does not make payments to the agent after a failure in the second period, since this only gives incentives for the agent to shirk. Moreover, the principal does not make payments to the agent after a success in the first period for two reasons. First, rewarding first-period success gives the agent incentives to employ the conventional work method in the first period, since the initial expected probability $E[p_2]$ of success with the new work method is lower than the probability p_1 of success with the conventional work method. Second, in case of a success in the first period, additional information about the first-period action is provided by the second-period performance, since the expected probability of success with the new work method in the second period depends on the action taken by the agent in the first period. Delaying compensation to obtain this additional information is thus optimal. Although there are 27 incentive compatibility constraints, it is easy to see that only a few may bind. The relevant incentive compatibility constraints are

$$(p_1 - p_0)w_{FS} \geq c_1 \qquad (\text{IC}_{\langle 2\, {}^2_0 \rangle})$$

$$(E[p_2]E[p_2|S,2] - p_0^2)w_{SS} - (E[p_2] - p_0)w_F - (E[p_2] - p_0)p_1 w_{FS} \geq c_2 + E[p_2](c_2 - c_1) + p_0 c_1 \quad (\text{IC}_{\langle 0 \, {}^0_1 \rangle})$$

$$(E[p_2]E[p_2|S,2] - p_0 p_1)w_{SS} - (E[p_2] - p_0)w_F - (E[p_2] - p_0)p_1 w_{FS} \geq c_2 + E[p_2](c_2 - c_1) \quad (\text{IC}_{\langle 0 \, {}^1_1 \rangle})$$

$$(E[p_2]E[p_2|S,2] - p_1^2)w_{SS} + (p_1 - E[p_2])w_F + (p_1 - E[p_2])p_1 w_{FS} \geq (1 + E[p_2])(c_2 - c_1) \quad (\text{IC}_{\langle 1 \, {}^1_1 \rangle})$$

The first three incentive compatibility constraints are associated with shirking. The last incentive compatibility constraint is associated with exploitation. One important thing to note is that w_F enters with a positive sign on the left hand side of the incentive compatibility constraint associated with exploitation. Rewarding the agent for first-period failures may be useful to prevent the agent from exploiting, since the initial expected probability $(1-E[p_2])$ of failure when the agent employs the new work method is higher than the probability $(1 - p_1)$ of failure when the agent employs the conventional work method.

The first incentive compatibility constraint is always binding. To prevent the agent from shirking in the second period after a failure in the first period, the principal pays $w_{FS} = \alpha_1$ to the agent just as in standard principal-agent models. It remains to discuss how the principal uses w_{SS} and w_F to induce the agent to experiment with the new work method.

If $c_2/c_1 < \beta_2$, then exploitation is too costly for the agent. Only incentive compatibility constraints associated with shirking are binding. To prevent the agent from shirking in the first period and in the second period after a success in the first period, the principal pays $w_{SS} = \alpha_2$ to the agent.

If $c_2/c_1 \geq \beta_2$, then exploitation is not too costly for the agent. The incentive compatibility constraint associated with exploitation is binding. To prevent exploitation, the principal can either reward the agent for failure in the first period or reward the agent for two consecutive successes. The principal's choice between these two instruments depends on whether exploration is moderate or radical. With moderate exploration, it is cheaper for the principal to provide incentives through w_{SS}, since two consecutive success are a stronger signal that the agent explored and not exploited than a failure in the first period. With radical exploration, it is cheaper for the principal to provide incentives through w_F, since a failure in the first period is a stronger signal that the agent explored and not exploited than two consecutive successes. Rewarding the agent for failure, however, induces the agent to shirk in the first period. To prevent shirking, delayed compensation w_{SS} must also be used.

Figure 2 shows the optimal contract that implements exploration for different values of c_2/c_1 under the base case parameters. The optimal contract that implements exploration

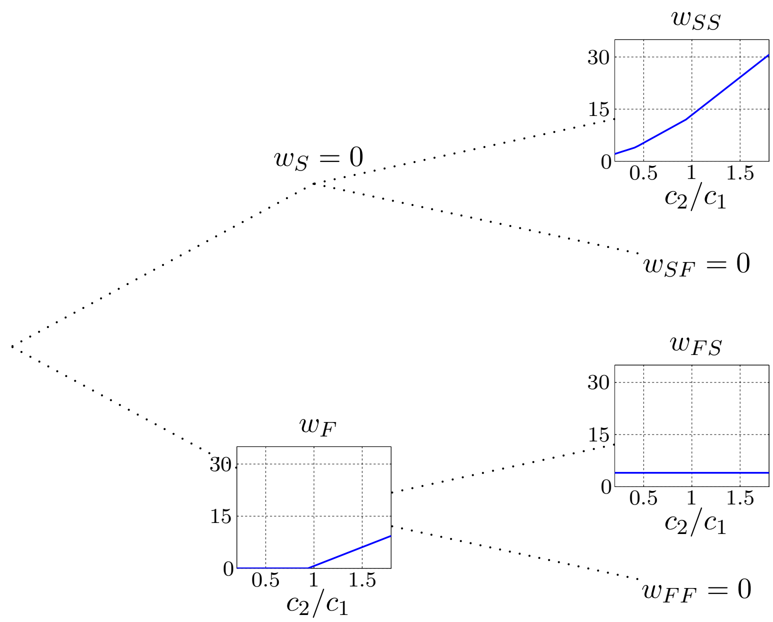

Figure 2: The optimal contract that implements exploration under the base parameters.

rewards long-term success, but not short-term success. On the contrary, it may even reward short-term failure. This safety-net is provided even though the agent is risk-neutral. The intuition is that if the agent is not protected against failures, then the agent may prefer to exploit in order to avoid failures.

An alternative way to interpret the optimal contract that implements exploration is to look at how it compensates different performance paths. The total compensation $w_F + w_{FS}$ when performance is FS is higher than the total compensation $w_S + w_{SF}$ when performance is SF. An agent who recovers from failure has a higher compensation than an agent who obtains short-lived success. Rewards are thus contingent on the performance path, and not only on the number of successes or failures obtained by the agent. If $w_F > 0$, then the total compensation $w_F + w_{FF}$ when performance is FF is higher than the total compensation $w_S + w_{SF}$ when performance is SF. Even an agent that fails twice may have a higher compensation than an agent that obtains short-lived success. Because of the risky nature of exploration, failing twice may be a stronger signal for the principal that the agent explored and not exploited than obtaining a short-lived success.

Some principal-agent models assume that the agent can destroy output. In a static setting, this assumption implies that the optimal contract is non-decreasing. In a dynamic setting, however, this is not necessarily true. For example, in the model developed here, setting $p_0 = 0$ will have the same effect as allowing the agent to destroy output. Still, from Proposition 7, the optimal contract that implements exploration may have $w_S < w_F$. Under this contract, if the agent decides to destroy output at the end of the first period to obtain

w_F, the agent foregoes the opportunity of earning w_{SS} in the second period.

4.3 The Principal's Choice Between Exploration and Exploitation

The two previous subsections studied the optimal contracts that motivate exploration and exploitation. This subsection studies the choice of the principal between motivating exploration and exploitation. In particular, it investigates the distortions that arise due to agency problems.

In the agency model studied here, the principal chooses the action plan $\langle {}_{i}{}^{j}_{k} \rangle$ that maximizes his expected profit:

$$\Pi(\langle {}_{i}{}^{j}_{k} \rangle) = R(\langle {}_{i}{}^{j}_{k} \rangle) - W(\vec{w}(\langle {}_{i}{}^{j}_{k} \rangle), \langle {}_{i}{}^{j}_{k} \rangle).$$

Therefore, the principal chooses exploration over exploitation if and only if

$$R(\langle {}_{2}{}^{2}_{1} \rangle) - W(\vec{w}(\langle {}_{2}{}^{2}_{1} \rangle), \langle {}_{2}{}^{2}_{1} \rangle) > R(\langle {}_{1}{}^{1}_{1} \rangle) - W(\vec{w}(\langle {}_{1}{}^{1}_{1} \rangle), \langle {}_{1}{}^{1}_{1} \rangle)$$

If there were no agency problems, however, it would be optimal for the principal to choose exploration over exploitation if and only if

$$R(\langle {}_{2}{}^{2}_{1} \rangle) - C(\langle {}_{2}{}^{2}_{1} \rangle) > R(\langle {}_{1}{}^{1}_{1} \rangle) - C(\langle {}_{1}{}^{1}_{1} \rangle)$$

This corresponds to the first-best decision criterion. The goal here will be characterize the distortions relative to the first-best decision criterion that are produced by agency problems. This leads to the following definition:

Definition 2 *The principal is biased against exploration if*

$$W(\vec{w}(\langle {}_{2}{}^{2}_{1} \rangle), \langle {}_{2}{}^{2}_{1} \rangle) - C(\langle {}_{2}{}^{2}_{1} \rangle) > W(\vec{w}(\langle {}_{1}{}^{1}_{1} \rangle), \langle {}_{1}{}^{1}_{1} \rangle) - C(\langle {}_{1}{}^{1}_{1} \rangle)$$

and the principal is biased towards exploration if

$$W(\vec{w}(\langle {}_{2}{}^{2}_{1} \rangle), \langle {}_{2}{}^{2}_{1} \rangle) - C(\langle {}_{2}{}^{2}_{1} \rangle) < W(\vec{w}(\langle {}_{1}{}^{1}_{1} \rangle), \langle {}_{1}{}^{1}_{1} \rangle) - C(\langle {}_{1}{}^{1}_{1} \rangle)$$

The principal is biased against (towards) exploration when the extra cost of motivating exploration is greater (lower) than the extra cost of motivation exploitation. The following proposition establishes conditions under which the principal is biased against or towards exploration.

Proposition 3 *The principal is biased against exploration if $c_2/c_1 > \beta_2$ and is biased towards exploration if $c_2/c_1 < \beta_2$.*

The intuition for the result is as follows. If $c_2/c_1 < \beta_2$, only shirking constraints are binding when implementing exploration. With learning the signal observed in the second period provides information about the action taken by the agent in the first period and therefore exploration is relatively cheaper to implement than exploitation. If $c_2/c_1 > \beta_2$, however, the exploitation constraint binds when implementing exploration, making exploration relatively more expensive to implement than exploitation.

5 Lack of Commitment

In contrast to the previous section, I now assume that the principal cannot commit to a long-term contract. In each period, the principal can only offer the agent a short-term contract specifying the agent's wages contingent on the current period performance. The problem is similar to the one proposed in Section 3, except that there are additional constraints to guarantee that the principal is willing to keep the promised wages in the second period.

Fudenberg, Holmstrom, and Milgrom (1990) provide conditions under which a sequence of short-term contracts perform just as well as the optimal long-term contract. The model proposed here violates two of these conditions. First, there may not be common knowledge of technology. With learning through experimentation, the agent may be better informed than the principal about the technology in the second period, since first-period actions affect second-period expected probability of success. Second, the utility frontier may not be downward sloping, since the agent has limited liability.

Proposition 4 *The optimal contract $\vec{w}_1$ that implements exploitation, derived in Proposition 1, can be realized through a sequence of short-term contracts.*

To implement exploitation, a sequence of short-term contracts performs just as well as the optimal long-term contract, because the optimal long-term contract that implements exploitation derived in Proposition 1 relies only on short-term incentives. Commitment is thus irrelevant to implement exploitation.

The following definition will be useful in stating Proposition 5:

$$\beta_5 = \frac{(E[p_2] - p_0)(1 + p_1)}{(p_1 - p_0)\left(1 + p_1 \frac{E[p_2]-p_0}{E[p_2|S,2]-p_0}\right)}.$$

Proposition 5 *The optimal contract $\vec{w}_2$ that implements exploration, derived in Proposition 2, cannot be replicated by a sequence of short-term contracts. Moreover, if*

- $c_2/c_1 \geq \beta_5$, *then exploration is not implementable via short-term contracts.*

- *$c_2/c_1 < \beta_5$, then the optimal sequence of short-term contracts $\vec{w}_5$ that implements exploration is such that*

$$w_S = \frac{c_2}{E[p_2] - p_0} - p_0 w_{SS} + p_0 w_{FS},$$
$$w_F = w_{SF} = w_{FF} = 0,$$
$$w_{SS} = \frac{c_2}{E[p_2|S,2] - p_0},$$
$$w_{FS} = \frac{c_1}{p_1 - p_0}.$$

Without commitment, the principal can only use short-term incentives to implement exploration. When $c_2/c_1 \geq \beta_5$, short-term incentives are not enough to induce exploration. If the principal rewards the agent for success in the first period, then the agent employs the conventional work method, which is relatively cheaper and yields a higher probability of success than the new work method. If, on the contrary, the principal rewards the agent for failure in the first period, then the agent shirks, which is cheaper and yields a higher probability of failure than the new work method. Therefore, if $c_2/c_1 \geq \beta_5$, exploration cannot be implemented with a sequence of short-term contracts.[7] When $c_2/c_1 < \beta_5$, short-term incentives may be enough to implement exploration. If the principal rewards the agent for success in the first period, it is too costly for the agent to employ the conventional work method. Exploration may thus be implementable with a sequence of short-term contracts. However, the cost $W(\vec{w}_5, \langle 2\,{}^2_1 \rangle)$ of implementing exploration with short-term contracts is higher than the cost $W(\vec{w}_2, \langle 2\,{}^2_1 \rangle)$ of implementing exploration with a long-term contract. When a long-term contract is used, the principal can wait until the second period to pay the agent, gathering more information about the agent's first period action.

Figure 3 compares the cost of implementing exploration when the principal can and cannot commit to a long-term contract. Exploration is implementable via a sequence of short-term contracts only if c_2/c_1 is low. Even if this is the case, the cost $W(\vec{w}_5, \langle 2\,{}^2_1 \rangle)$ of implementing exploration with short-term contracts is higher than the cost $W(\vec{w}_2, \langle 2\,{}^2_1 \rangle)$ of implementing exploration with a long-term contract.

This section contrasts the effect of lack of commitment on the implementation of exploration and exploitation. To implement exploitation, a sequence of short-term contracts performs as well as the optimal long-term contract. On the other hand, to implement exploration, the optimal long-term contract performs better than any sequence of short-term contracts. For some parameters, it is even impossible to implement exploration with

[7] Hermalin and Katz (1991) show that an action is implementable if there does not exist a randomization over actions that induces the same density over outcome and costs less to the agent. When $c_2/c_1 \geq \beta_5$, a randomization over actions 0 and 1 induces the same density over first-period outcome as action 2 and costs less to the agent.

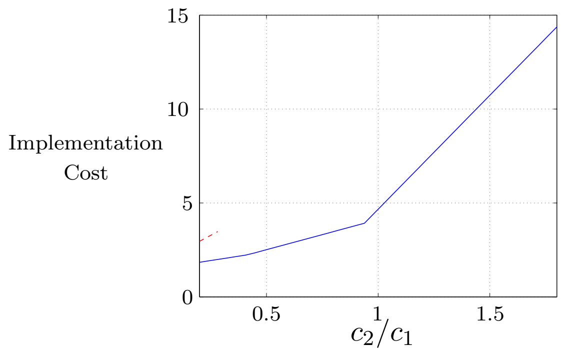

Figure 3: Cost of implementing exploration when the principal can (solid line) and cannot (dashed line) commit to a long-term contract under the base parameters.

a sequence of short-term contracts. These results show the importance of commitment when implementing exploration. In practice, commitment to a long-term contract may be achieved through explicit contracts, such as stock options or vesting stock, or through implicit contracts, based on reputation.

6 Termination

In this section, I allow the principal to terminate the agent after a failure in the first period. The principal may use termination as a screening device, firing the agent if it is not worthwhile to keep him in the second period. In addition to that, the principal may use termination as a disciplinary device to induce the agent to take the appropriate action in the first period.

I derive the optimal contracts that implement exploitation with termination and exploration with termination. I then study when it is optimal for the principal to implement exploitation with termination instead of exploitation, and exploration with termination instead of exploration. Exploitation with termination is represented by action plan $\langle {}_1{}^{1}_{t} \rangle$, and exploration with termination is represented by action plan $\langle {}_2{}^{2}_{t} \rangle$, where t means that the principal terminates the agent after a failure in the first period. For simplicity, the agent's outside wages after termination are zero.[8] The principal's expected revenues when implementing exploration with termination and exploitation with termination are given by $R(\langle {}_1{}^{1}_{t} \rangle)$ and $R(\langle {}_2{}^{2}_{t} \rangle)$, which may incorporate, for example, the possibility of hiring a replacement agent after termination.

Proposition 6 derives the optimal contract that implements exploitation with termination.

[8]In this context, implementing action plan $\langle {}_i{}^{j}_{t} \rangle$ is the same as implementing action plan $\langle {}_i{}^{j}_{0} \rangle$ with $w_{FF} = w_{FS} = 0$.

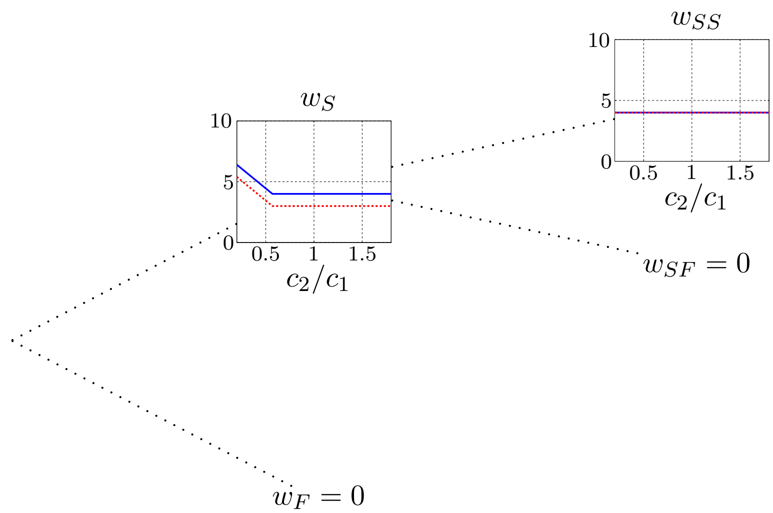

Figure 4: The optimal contracts that implement exploitation (solid line) and exploitation with termination (dashed line) under the base parameters.

Proposition 6 *The optimal contract $\vec{w}_6$ that implements exploitation with termination is such that*

$$w_F = w_{SF} = 0,$$

$$w_{SS} = \alpha_1,$$

and

$$w_S = (1 - p_0)\alpha_1 + \frac{c_1}{(p_1 - p_0)(p_1 - E[p_2])}\left(\beta_1 - \frac{c_2}{c_1}\right)^+ .$$

The agent is more likely to fail in the first period if he shirks or employs the new work method than if he employs the conventional work method. To avoid failure, and consequently termination, the agent has more incentives to employ the conventional work method in the first period. Therefore, the principal needs to pay the agent lower first-period wages to implement exploitation with termination than to implement exploitation. This result is similar to Stiglitz and Weiss (1983), where the principal uses termination to help inducing the agent to exert effort. Figure 4 compares the optimal contracts that implement exploitation and exploitation with termination for different values of c_2/c_1 under the base case parameters.

I now compare the total expected profits of the principal when he implements exploitation with the total expected profits of the principal when he implements exploitation with termination. It is optimal for the principal to implement exploitation with termination instead of exploitation if

$$R(\langle {}_1{}^1_1 \rangle) - R(\langle {}_1{}^1_t \rangle) < W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) - W(\vec{w}_6, \langle {}_1{}^1_t \rangle). \tag{7}$$

To keep the agent working in the second period after a failure in the first period, the expected payments from the principal to the agent are equal to $(1-p_1)p_1\alpha_1$. It is thus ex post efficient for the principal to terminate the agent after a failure in the first period if

$$R(\langle 1\,{}^{1}_{1}\rangle) - R(\langle 1\,{}^{1}_{t}\rangle) < (1-p_1)p_1\alpha_1. \tag{8}$$

When (8) holds, the benefits from inducing the agent to work in the second period after a failure in the first period are lower than the expected payments that the principal must make to the agent after a failure in the first period to keep the agent working in the second period.

Definition 3 *There is excessive termination with exploitation if*

$$W(\vec{w}_1, \langle 1\,{}^{1}_{1}\rangle) - W(\vec{w}_6, \langle 1\,{}^{1}_{t}\rangle) > (1-p_1)p_1\alpha_1.$$

and there is excessive continuation with exploitation if

$$W(\vec{w}_1, \langle 1\,{}^{1}_{1}\rangle) - W(\vec{w}_6, \langle 1\,{}^{1}_{t}\rangle) < (1-p_1)p_1\alpha_1.$$

There is excessive termination with exploitation if the actual threshold for termination is higher than the ex post efficient threshold for termination. There is excessive continuation with exploitation if the actual threshold for termination is lower than the ex post efficient threshold for termination. Excessive continuation or termination may arise because the termination policy affects the incentives for the agent's first-period action.

Corollary 1 *There is excessive termination with exploitation.*

As shown in Proposition 6, termination acts as a disciplinary device so that to implement exploitation with termination the principal needs to pay the agent lower first-period wages than to implement exploitation. There is excessive termination with exploitation because the lower wages paid to the agent offset the losses from excessive termination.

Proposition 7 derives the optimal contract that implements exploration with termination. The following definitions will be useful in stating Proposition 7:

$$\alpha_7 = \max_{\tilde{j}\in\{0,1\}} \frac{(1+E[p_2])c_2 - p_0 c_{\tilde{j}}}{E[p_2]E[p_2|S,2] - p_0 E[p_{\tilde{j}}]},$$

$$\beta_7 = \frac{(E[p_2]E[p_2|S,2] - p_0 p_1) + E[p_2](p_1 E[p_2|S,2] - p_0 E[p_2|S,2])}{(p_1^2 - p_0) + E[p_2](p_1^2 - p_0)}.$$

Proposition 7 *The optimal contract $\vec{w}_7$ that implements exploration with termination is such that*

$$w_S = w_{SF} = 0.$$

If exploration is moderate, then $w_F = 0$, and

$$w_{SS} = \alpha_7 + \frac{p_1 - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1 + E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1^2} \left(\frac{c_2}{c_1} - \beta_7 \right)^+ .$$

If exploration is radical, then

$$w_F = \frac{p_1(1 + E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_7 \right)^+$$

and

$$w_{SS} = \alpha_7 + \frac{E[p_2] - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1 + E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_7 \right)^+ .$$

The effects of termination on the incentives for the agent to employ the new work method in the first period will depend on the relative costs c_2/c_1 of the new and conventional work methods. If $c_2/c_1 \geq \beta_7$, then the incentive compatibility constraint associated with exploitation with termination is binding. Termination makes it harder to provide incentives for the agent to employ the new work method in the first period, since to avoid failure and termination the agent has more incentives to employ the conventional work method in the first period. If $c_2/c_1 < \beta_7$, then the incentive compatibility constraint associated with shirking is binding. Termination makes it easier to provide incentives for the agent to employ the new work method in the first period, since to avoid failure and termination the agent has less incentives to shirk in the first period.

Figure 5 compares the optimal contracts that implement exploration and exploration with termination for different values of c_2/c_1 under the base case parameters. If c_2/c_1 is high, the principal pays higher wages w_F to implement exploration with termination than to implement exploration. If c_2/c_1 is low, the principal pays lower wages w_{SS} to implement exploration with termination than to implement exploration.

I now compare the total expected profits of the principal when he implements exploration with the total expected profits of the principal when he implements exploration with termination. It is optimal for the principal to implement exploration with termination instead of exploration if

$$R(\langle 2\,{}^{2}_{1} \rangle) - R(\langle 2\,{}^{2}_{t} \rangle) < W(\vec{w}_2, \langle 2\,{}^{2}_{1} \rangle) - W(\vec{w}_7, \langle 2\,{}^{2}_{t} \rangle)$$

To keep the agent working in the second period after a failure in the first period, the expected payments from the principal to the agent are equal to $(1 - p_1)p_1\alpha_1$. It is thus ex post efficient for the principal to terminate the agent after a failure in the first period if

$$R(\langle 2\,{}^{2}_{1} \rangle) - R(\langle 2\,{}^{2}_{t} \rangle) < (1 - E[p_2])p_1\alpha_1. \tag{9}$$

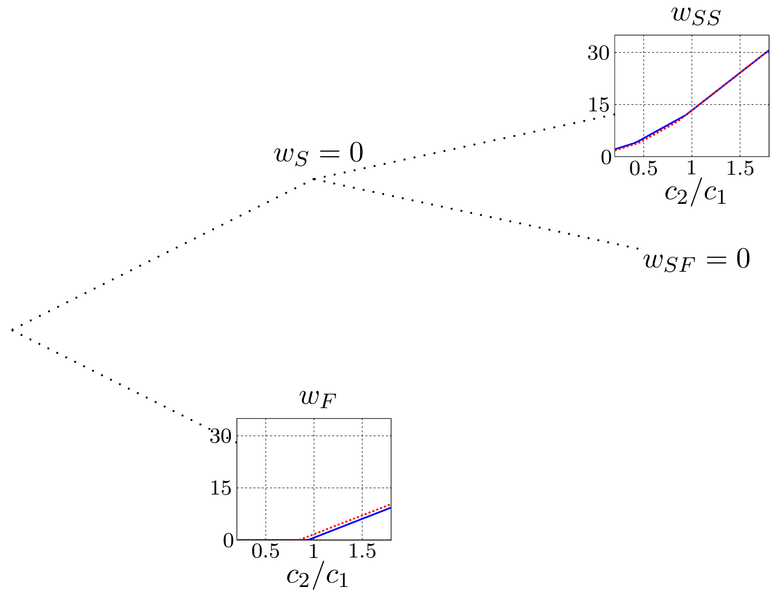

Figure 5: The optimal contract that implements exploration (solid line) and exploration with termination (dashed line) under the base parameters.

When (9) holds, the benefits from inducing the agent to work in the second period after a failure in the first period are lower than the expected payments that the principal must make to the agent after a failure in the first period to keep the agent working in the second period.

Definition 4 *There is excessive termination with exploration if*

$$W(\vec{w}_2, \langle 2\,{}^{2}_{1}\rangle) - W(\vec{w}_7, \langle 2\,{}^{2}_{t}\rangle) > (1 - E[p_2])p_1\alpha_1,$$

and there is excessive continuation with exploration if

$$W(\vec{w}_2, \langle 2\,{}^{2}_{1}\rangle) - W(\vec{w}_7, \langle 2\,{}^{2}_{t}\rangle) < (1 - E[p_2])p_1\alpha_1.$$

There is excessive termination with exploration if the actual threshold for termination is higher than the ex post efficient threshold for termination. There is excessive continuation with exploration if the actual threshold for termination is lower than the ex post efficient threshold for termination. Excessive continuation or termination may arise because the termination policy affects the incentives for the agent's first-period action.

Corollary 2 investigates the conditions under which there is excessive termination with exploration or excessive continuation with exploration. The following definitions will be useful in stating Corollary 2:

$$\kappa_m \equiv \frac{(p_1 - E[p_2])(E[p_2]E[p_2|S,2] - p_1p_0)}{(p_1 - E[p_2])(E[p_2]E[p_2|S,2] - p_1p_0) + (E[p_2] - p_0)(E[p_2]E[p_2|S,2] - p_1^2)},$$

$$\kappa_e \equiv \frac{(1 - E[p_2])(E[p_2]E[p_2|S,2] - p_0p_1)}{(1 - E[p_2])(E[p_2]E[p_2|S,2] - p_0p_1) + E[p_2]E[p_2|S,2](E[p_2] - p_0)}.$$

Corollary 2 *If* $c_2/c_1 < \max(\kappa_m, \kappa_e)\beta_2 + (1 - \max(\kappa_m, \kappa_e))\beta_7$*, then there is excessive termination with exploration. If* $c_2/c_1 > \max(\kappa_m, \kappa_e)\beta_2 + (1 - \max(\kappa_m, \kappa_e))\beta_7$*, then there is excessive continuation with exploration.*

As shown in Proposition 7, the effects of termination on the incentives for the agent to employ the new work method in the first period depend on c_2/c_1. For low values of c_2/c_1, the agent is inclined to shirk. The threat of termination allows the principal to pay the agent lower wages to prevent shirking, offsetting the losses from excessive termination. For high values of c_2/c_1, the agent is inclined to exploit. Excessive continuation allows the principal to pay the agent lower wages in the first period, offsetting the losses from excessive continuation.

As shown in Corollary 2, there is excessive continuation with exploration even if exploration is moderate. This is in contrast to the results in Proposition 2 which say that there is reward for failure only if exploration is radical. With moderate exploration, the principal does not reward the agent for failure because it is cheaper to use rewards for long-term success to induce exploration. However, the surplus the agent obtains in the second period after a failure in the first period still provides incentives for the agent to explore when c_2 is high relative to c_1.

This section contrasts the optimal termination policies when implementing exploitation and exploration. Similarly to models of repeated effort, there is excessive termination when implementing exploitation. On the other hand, depending on which constraints are binding, there may be excessive termination or excessive continuation when implementing exploration. There is excessive termination if only shirking constraints are binding, while there is excessive continuation if the exploitation constraint is binding. To sum up, termination is useful to prevent shirking but it is may be harmful when implementing exploration as it may induce exploitation from the agent.

7 Feedback

In this section, I study what happens if the principal is better able than the agent to evaluate performance. This could be relevant, for example, in studying the relation between a venture capitalist and an entrepreneur, in which the venture capitalist knows more about the commercial value of the enterprise than the entrepreneur. Also, firms often have better information about the market performance of products developed by their employees. The focus of the section will be on whether the principal should provide feedback on performance to the agent.

Feedback, or interim performance evaluation, has received little attention in the economics literature. In a setting where the principal's problem is to induce the agent to exert effort, Lizzeri, Meyer, and Persico (2002) and Fuchs (2007) find that it is optimal for the principal not to reveal information about performance to the agent.[9] Ederer (2008) shows that feedback may be useful when the agent is uncertain about his ability. Outside a principal-agent setting, Ray (2004) develops a model in which interim performance evaluation serves the purpose of screening bad projects. Here, the optimal provision of feedback will depend on whether the principal wants to implement exploration or exploitation.

I now assume that the principal privately observes interim performance at the end of the first period, yet the performance path is publicly observable at the end of the second period. If the principal does not reveal interim performance realizations, then only incentive compatibility constraints $\mathrm{IC}_{\langle i\,{}^{j}_{k}\rangle}$ where $j = k$ need to be satisfied, since without feedback the agent cannot adjust his action according to the realization of first-period performance. However, for the same reason, only action plans $\langle i\,{}^{j}_{k}\rangle$ with $j = k$ can be implemented without feedback. Therefore, if the action plan to be implemented involves repetitive actions, then it is optimal for the principal not to provide feedback on performance. On the other hand, if the action plan to be implemented requires adjustments in action depending on the realized interim performance, then feedback on performance must be provided.

The following definitions will be useful in stating Proposition 8:

$$\alpha_8 = \frac{2c_1}{p_1^2 - p_0^2},$$

$$\beta_8 = \frac{E[p_2]E[p_2|S,2] - p_0^2}{p_1^2 - p_0^2}.$$

Proposition 8 *To implement exploitation, it is optimal for the principal not to provide feedback on performance to the agent. The optimal contract that implements exploitation without feedback is such that*

$$w_S = w_F = w_{FF} = 0,$$

$$w_{SF} = w_{FS} = \frac{(p_1 + p_0)c_1}{p_0(p_1 - E[p_2]) + E[p_2](E[p_2|S,2] - p_1)}\left(\beta_8 - \frac{c_2}{c_1}\right)^+,$$

and

$$w_{SS} = \alpha_8 - \frac{2(1 - p_1 - p_0)c_1}{p_0(p_1 - E[p_2]) + E[p_2](E[p_2|S,2] - p_1)}\left(\beta_8 - \frac{c_2}{c_1}\right)^+.$$

[9]This result is closely related to the results of Abreu, Milgrom, and Pearce (1991) on the reusability of punishments.

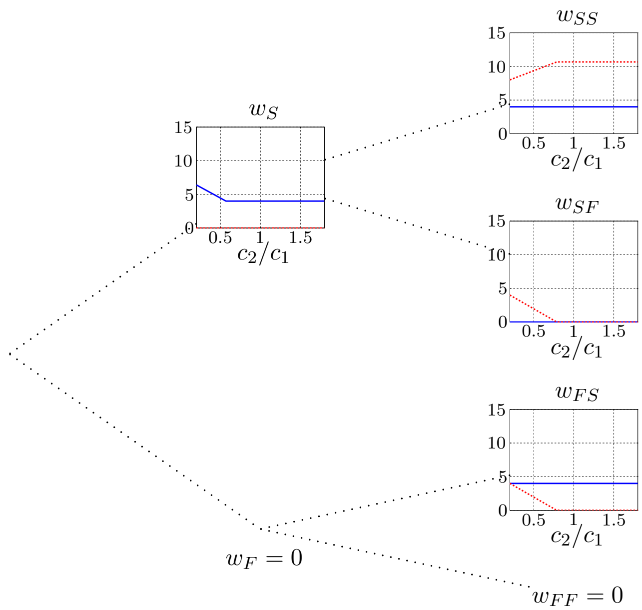

Figure 6: The optimal contract that implements exploitation with (solid line) and without (dashed line) feedback under the base parameters.

If the principal does not provide feedback, then incentive compatibility constraints associated with exploration, shirking in the second period in case of a success in the first period, and shirking in the second period in case of failure in the first period, which are binding when interim performance is publicly observable, can be ignored. Therefore, it is less costly to implement exploitation if information about interim performance is not revealed to the agent. The relevant incentive compatibility constraints are:

$$(p_1^2 - p_0^2)w_{SS} + (p_1(1-p_1) - p_0(1-p_0))w_{SF} + ((1-p_1)p_1 + (1-p_0)p_0)w_{FS} \geq 2c_1 \quad (\mathrm{IC}_{\langle 0 \, {}^0_0 \rangle})$$

$$(p_1^2 - E[p_2]E[p_2|S,2])w_{SS} + (p_1(1-p_1) - E[p_2](1-E[p_2|S,2]))w_{SF} + ((1-p_1)p_1 + (1-E[p_2])E[p_2|F,2])w_{FS} \geq 2(c_1 - c_2) \quad (\mathrm{IC}_{\langle 2 \, {}^2_2 \rangle})$$

The optimal contract that implements exploitation without feedback has $w_{SS} \geq w_{SF} = w_{FS} \geq w_{FF} = 0$. If $c_2/c_1 > \beta_8$, then $\mathrm{IC}_{\langle 0 \, {}^0_0 \rangle}$ is binding, and incentives are provided through w_{SS} only. If $c_2/c_1 < \beta_8$, then $\mathrm{IC}_{\langle 2 \, {}^2_2 \rangle}$ is binding and $w_{SS} > w_{SF} = w_{FS} > 0$, since providing incentives only through w_{SS} could induce the agent to try the new work method. Figures 6 and 7 compare the optimal contracts and the costs to implement exploitation with and without feedback under the base case parameters.

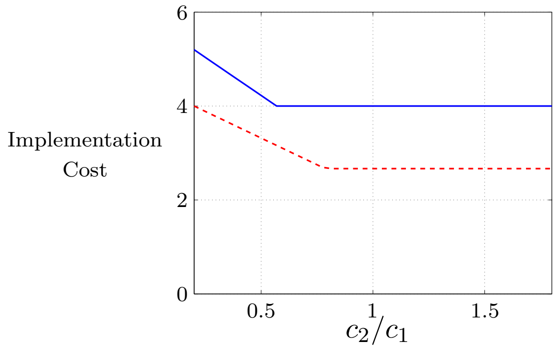

Figure 7: Cost of implementing exploitation with (solid line) and without (dashed line) feedback under the base parameters.

Proposition 9 *To implement exploration, the principal must provide feedback to the agent. The optimal contract $\vec{w}_9$ that implements exploration when the principal is better able than the agent to evaluate performance is the same as the optimal contract $\vec{w}_2$ that implements exploration derived in Proposition* 2.

Feedback is essential to implement exploration. It allows for rapid and efficient experimentation. The function of feedback here is to provide information that improves the agent's future performance. No punishment is associated with feedback. On the contrary, for some parameters the agent is even rewarded in case of failure. If the agent is not protected against failures, then the agent is inclined to employ the conventional work method to avoid failures.

This section contrasts the feedback policy when implementing exploitation and exploration. It shows that, similarly to repeated-effort models, the principal should never provide feedback on performance to the agent when implementing exploitation, but should always provide timely feedback on performance to the agent when implementing exploration.

8 Applications

Management of Innovation Business consultants have recognized the potential hazards of standard pay-for-performance contracts to innovation. They advocate that a culture that allows freedom to experiment and tolerates failures is essential to motivate innovation.

As shown in Proposition 5, the ability to commit to a long-term contract is essential to encourage exploration. Modern corporations often rely on their corporate culture to overcome this commitment problem and encourage exploration. Promises made in the form of a corporate culture are enforced through reputation. From Proposition 2, a corporate culture that tolerates early failure and reward long-term success is optimal to motivate exploration.

Innovative organizations may also rely on explicit long-term contracts to overcome the commitment problem and induce exploration. For example, research departments in business or academic organizations often grant tenure to their researchers. Knowing that they will not lose their jobs, researchers are wiling to explore new research directions that are likely to fail, but may lead to breakthroughs. Even before obtaining tenure, researchers in academic organizations are usually given a period of time under which they cannot be terminated. From Corollary 2, by committing not to terminate researchers, research departments are able to motivate exploration. Researchers are also often given long-term incentives in the form of stock options and restricted stocks. Lerner and Wulf (2007) have found that more long-term incentives to the heads of research and development departments are associated with more heavily cited patents, while short-term incentives are unrelated to measures of innovation.

Executive Compensation and Corporate Governance In the context of the recent scandals in the American corporate sector, executive compensation has increasingly been criticized as excessive and not related to performance. This public outcry creates pressure for regulations that limit the use of stock options, golden parachutes, entrenchment, and option repricing.[10]

In an article on the state of U.S. corporate governance, Holmstrom and Kaplan (2003) alert for the risk of a regulatory overreaction by saying that

> . . . an effort to regulate the system so that such outrage will never again occur would be overly costly and counterproductive. It would lead to inflexibility and fear of experimentation. In today's uncertain climate, we probably need more organizational experimentation than ever. The New Economy is moving forward and, in order to exploit the potential efficiencies inherent in the new information technologies, new business models and new organizational structures are likely to be desirable and valuable. Enron was an experiment that failed. We should take advantage of its lessons not by withdrawing into a shell, but rather by improving control structures and corporate governance so that other promising experiments can be undertaken.

In fact, it is easy to see from Propositions 2 and 7 that the optimal contracts that provide incentives for exploration and exploration with termination can be implemented by combinations of stock options, option repricing, golden parachutes, and entrenchment. Stock options provide long-term incentives while golden parachutes protect the agent against early failures. Option repricing not only induces the agent to exert effort in case his stock

[10]See, for example, Bebchuk and Fried (2004) and "Rewards for Failure," *British DTI consultation*, June 2003.

options goes out of the money, but also induces the agent to employ the new work method in the first period as it protects the agent against early failures. Finally, as shown in Corollary 2, excessive continuation with exploration is sometimes optimal. One can interpret this as entrenchment, since the manager may keep his job even though it is ex post efficient for the firm to terminate the manager. These results suggest that regulations that limit the use of stock options, option repricing, golden parachutes, and entrenchment may just make it more difficult to motivate exploration, and can potentially have negative effects on innovation, and long-term growth.

The theory developed here suggests that these instruments should be more often used in situations in which exploration and innovation are important. One potentially interesting direction of research is to study if options, entrenchment, and golden parachutes are more common in firms and industries involved in innovation.

Previous studies, such as Lambert (1986), and Feltham and Wu (2001) have developed static models in which the optimal compensation that encourages risk-taking is convex, resembling a stock option. Other studies derived optimal contracts that, for different reasons than the one proposed here, involve golden parachutes, entrenchment, or option repricing. In a setting in which the manager observes a private signal about the future prospects of the firm, Inderst and Mueller (2006) and Rayo and Sapra (2008) show that stock options and golden parachutes may be optimal to induce the manager to reveal information to the board after bad outcomes. In an incomplete contracting framework, Almazan and Suarez (2003) show that a contract consisting of bonus and severance pay may be optimal to induce the incumbent manager to invest in firm-specific human capital when there is the threat that a better rival manager becomes available. In a setting where the only instruments available to the principal are at-the-money call options, Acharya, John, and Sundaram (2000) show that option repricing may be optimal because it motivates the agent to exert effort after poor performance. Atanassov (2008) and Sapra, Subramanian, and Subramanian (2008) study the effects of corporate governance on innovation.

Bankruptcy Laws and Entrepreneurship Bankruptcy laws in Europe and in the United States have recently been under debate. On one hand, to encourage entrepreneurial activity, the European Council issued in June of 2000 the “European Charter for Small Enterprises,”which states that

> . . . failure is concomitant with responsible initiative and risk-taking and must be mainly envisage as a learning opportunity.

The Charter declares that bankruptcy law reforms should become a clear priority for the Member States and that new bankruptcy laws should allow failed entrepreneurs a fresh start. On the other hand, after eight years of discussion, the U.S. Congress passed in April of 2005 a new creditor-friendly bankruptcy law, the "Bankruptcy Abuse and Consumer Protection Act," which makes it more difficult for insolvent debtors to obtain exemptions and discharge of obligations.

The model developed in this paper sheds light on the incentive effects of different bankruptcy laws. If the entrepreneur borrows money to undertake some project and the project fails, then the entrepreneur will not have the funds to pay his debts and will be insolvent. From Propositions 1 and 2, the optimal contracts that motivate exploration and exploitation are quite different in the way they treat insolvent debtors. The optimal contract that motivates exploration rewards the agent after failure. One can interpret this as a bankruptcy law based on the principle of a fresh start, as it provides the entrepreneur with generous exemptions and an immediate full discharge of debt, so that the entrepreneur keeps some surplus after failure. By protecting the entrepreneur against early failure, these bankruptcy laws make the entrepreneur more inclined to explore. On the other hand, the optimal contract that implements exploitation does not reward the agent after failure. One can interpret this as a bankruptcy law based on the principle of absolute priority. The creditor seizes the goods owned by the entrepreneur and discharge takes several years. The creditor may allow the entrepreneur to keep working after default if it is still profitable to do so, but the entrepreneur earns just enough money so that he does not shirk.

A natural question to ask is why governments impose a single mandatory bankruptcy law. By considering the incentives for exploration, this paper provides a potential explanation for this question. Due to knowledge spillovers and imperfect intellectual-property-rights (IPR) protection, individuals involved in exploratory activities cannot fully appropriate the economic value generated by the knowledge they produce. As argued by Nelson (1959), this leads to under-exploration when compared to the socially efficient level of exploration. One way to alleviate the under-exploration problem, is by imposing a debtor-friendly bankruptcy law.

There is a large literature on the design of bankruptcy laws. Based on standard models of incentives, Jensen (1991) and Aghion, Hart, and Moore (1992) are strong proponents of bankruptcy laws that respect the absolute priority of claims. Other papers have found beneficial effects of deviations from absolute priority. For example, Bebchuk and Picker (1993), and Berkovitch, Israel, and Zender show that deviations of absolute priority may encourage investments in firm-specific versus general human capital. Baird (1991) and Povel (1999) show that deviations of absolute priority induce the entrepreneur to reveal private information to creditors when bad outcomes occur.[11] Ayotte (2007) shows that a mandatory debtor friendly bankruptcy law may increase social welfare, because it prevents the monopolist bank from extracting too much surplus from the entrepreneur. Acharya

[11]Landier (2002) develops a model with multiple equilibria in which the stigma of failure may prevent entrepreneurs from abandoning bad projects.

and Subramanian (2009) analyze the effect of bankruptcy laws on entrepreneurship using cross-sectional and time series data of several countries. They find that debtor friendly bankruptcy laws lead to more innovation.

9 Additional Discussion

I assumed throughout the paper that the agent is risk-neutral and has limited liability. Results similar to the ones obtained here hold if the agent is risk-averse. The critical elements influencing the optimal contracts are the likelihood ratios between the different action plans, and not the agent's preferences. If the agent is risk-neutral, then the problem of finding the optimal contract that implements a given action plan simplifies to a linear programming problem. This allows me to focus on incentive issues rather than on risk-sharing issues.

For tractability, I restricted the analysis to a model with two periods and two possible outcomes in each period. Having more periods can strengthen the results obtained here. As discussed in Section 2, if the agent lives for multiple periods, the agent is willing to sacrifice even more output in the first period by employing the new work method, since the information learned in the first period can be used for a longer period of time. On the other hand, having multiple possible outcomes in each period may change some of the results. For example, if the new work method can produce a big success in the first period, then it is possible that the optimal contract that implements exploration rewards the big success in the first-period. Two considerations justify the restriction to two possible outcomes. First, most of the studies on innovation point to the high rate of failure in innovative projects as the fundamental difference between innovative and traditional projects. If this is indeed the case, even with multiple possible outcomes in each period, the principal will still rely on reward for early failures, as it is the cheapest way to distinguish exploration from exploitation. Second, if the agent is risk-averse, then both rewards for failure and rewards for big successes will be used. Since the probability of a big success in the first period when the agent employs the new work method is usually very low, we will often see more often in practice rewards for failure than rewards for big successes.

Lazear (1986) makes the distinction between input-based pay, where the principal compensates the agent based on the action taken by the agent, and output-based pay, where the principal compensates the agent based on the output produced by the agent. I assumed in this paper that the principal observes only the output produced by the agent, and consequently, can use only output-based pay. In many situations, however, a noisy signal about the action taken by the agent is publicly observable. One can show that if the principal observes a noisy signal about the agent's action, then the principal uses both input-based pay and output-based pay to compensate the agent. As the signal about the actions taken by the agent becomes more precise, the principal relies more on input-based pay, but still relies on output-based pay in the form studied in this paper. It is only in the extreme case in which the principal perfectly observes the actions taken by the agent that the principal does not rely on output-based pay.

10 Conclusion

This paper proposes a framework to study the incentives for innovation. In this framework, innovation is the result of learning through the exploration of untested approaches that are likely to fail. Because of that, the optimal incentive scheme that motivates exploration is fundamentally different from standard pay-for-performance schemes used to motivate effort. Tolerance (or even reward) for early failure, reward for long-term success, excessive continuation, commitment to a long-term incentive plan, and timely feedback on performance are all important ingredients to motivate exploration.

Practices such as the institution of tenure, golden parachutes, and debtor-friendly bankruptcy laws protect or even reward the agent when failure occurs. These practices are often criticized, because by protecting or rewarding the agent after poor performance, they undermine the incentive for the agent to exert effort. This paper shows that these practices may arise as part of an optimal incentive scheme that motivates exploration. Therefore, limiting their use may have adverse effects on innovation.

There are several potentially interesting extensions of the theoretical model proposed here. For example, if the agent has superior information about his own type, then contracts may be used to sort agents. This raises a new issue: what is the optimal menu of contracts that separates creative workers from shirkers and conventional workers? An additional extension to consider is the case of multiple agents. This raises another issue: what is the optimal balance between individual and team incentives to motivate exploration? Another issue that arises with multiple agent is the complementarity in their expertise. Biais and Perotti (2008), Hellman and Perotti (2007), and Stein (2008) are some of the papers that explore this topic. The interaction between this complementarity of expertise and learning through experimentation is an interesting area for future research.

The ideas presented here can also be tested empirically. One natural place to start is the experimental evidence in psychology on the detrimental effects of reward on performance. Revisiting these experiments with different reward structures seems to be a promising direction of research. It would be interesting to see the effects of reward for early failure, long-term incentives, feedback and termination on creativity and performance in these experiments.

11 Appendix

The following definitions will be useful in stating the incentive compatibility constraints:

$$V_S(\vec{w}, \langle {}_i{}^j_k \rangle) = w_S + E[p_j|S,i]w_{SS} + (1 - E[p_j|S,i])w_{SF},$$

$$V_F(\vec{w}, \langle {}_i{}^j_k \rangle) = w_F + E[p_k|F,i]w_{FS} + (1 - E[p_k|F,i])w_{FF}.$$

Proof of Proposition 1: The optimal contract $\vec{w}$ that implements action plan $\langle {}_1{}^1_1 \rangle$ satisfies the following incentive compatibility constraints:

$$\begin{aligned}(p_1 - E[p_i])(V_S(\vec{w}, \langle {}_1{}^1_1 \rangle) - V_F(\vec{w}, \langle {}_1{}^1_1 \rangle)) \\ + E[p_i](p_1 - E[p_j|S,i])(w_{SS} - w_{SF}) \\ + (1 - E[p_i])(p_1 - E[p_k|F,i])(w_{FS} - w_{FF}) \geq \\ (c_1 + p_1 c_1 + (1-p_1)c_1) - (c_i + E[p_i]c_j + (1 - E[p_i])c_k). \quad (\mathrm{IC}_{\langle {}_i{}^j_k \rangle})\end{aligned}$$

First, I show that $w_F = w_{FF} = w_{SF} = 0$. Suppose $w_F > 0$ or $w_{FF} > 0$. A contract $\vec{w}'$ that is the same as $\vec{w}$ but has $w'_F = 0$ and $w'_{FF} = 0$ satisfies all $\mathrm{IC}_{\langle {}_i{}^j_k \rangle}$ and has $W(\vec{w}', \langle {}_1{}^1_1 \rangle) < W(\vec{w}, \langle {}_1{}^1_1 \rangle)$. Suppose now that $w_{SF} > 0$. Let the contract $\vec{w}'$ be the same as $\vec{w}$ except that $w'_{SF} = 0$, $w'_{SS} = w_{SS} - w_{SF}$ and $w'_S = w_S + w_{SF}$. The contract $\vec{w}'$ satisfies all $\mathrm{IC}_{\langle {}_i{}^j_k \rangle}$, $W(\vec{w}', \langle {}_1{}^1_1 \rangle) = W(\vec{w}, \langle {}_1{}^1_1 \rangle)$, but $\vec{w}'$ pays the agent earlier than $\vec{w}$.

I now argue that some incentive compatibility constraints are redundant. If $(i,j) \neq (1,1)$, then it follows from $\mathrm{IC}_{\langle {}_1{}^1_0 \rangle}$ and $\mathrm{IC}_{\langle {}_i{}^j_1 \rangle}$ that $\mathrm{IC}_{\langle {}_i{}^j_0 \rangle}$ are redundant. If $(i,k) \neq (1,1)$, then it follows from $\mathrm{IC}_{\langle {}_1{}^0_1 \rangle}$ and $\mathrm{IC}_{\langle {}_i{}^1_k \rangle}$ that $\mathrm{IC}_{\langle {}_i{}^0_k \rangle}$ are redundant. If $\langle {}_i{}^j_k \rangle \neq \langle {}_2{}^2_1 \rangle$ and either $i = 2$, $j = 2$, or $k = 2$, then it follows from $c_2/c_1 \geq (E[p_2] - p_0)/(p_1 - p_0)$ that $\mathrm{IC}_{\langle {}_i{}^j_k \rangle}$ is redundant. Rewriting the incentive compatibility constraints that are not redundant:

$$(p_1 - p_0)w_{SS} \geq c_1 \quad (\mathrm{IC}_{\langle {}_1{}^0_1 \rangle})$$

$$(p_1 - p_0)w_{FS} \geq c_1 \quad (\mathrm{IC}_{\langle {}_1{}^1_0 \rangle})$$

$$(p_1 - p_0)w_S + (p_1^2 - p_0 p_1)w_{SS} - (p_1^2 - p_0 p_1)w_{FS} \geq c_1 \quad (\mathrm{IC}_{\langle {}_0{}^1_1 \rangle})$$

$$\begin{aligned}(p_1 - E[p_2])w_S + (p_1^2 - E[p_2]E[p_2|S,2])w_{SS} - (p_1^2 - E[p_2]p_1)w_{FS} \geq \\ c_1 - c_2 + E[p_2](c_1 - c_2) \quad (\mathrm{IC}_{\langle {}_2{}^2_1 \rangle})\end{aligned}$$

I now show that $\mathrm{IC}_{\langle {}_1{}^0_1 \rangle}$ and $\mathrm{IC}_{\langle {}_1{}^1_0 \rangle}$ are binding. If that is not the case, then either

$$\Delta_1 \equiv w_{SS} - \frac{c_1}{p_1 - p_0} > 0$$

or

$$\Delta_2 \equiv w_{SF} - \frac{c_1}{p_1 - p_0} > 0$$

Let $\vec{w}'$ be the same as $\vec{w}$ except that $w'_{SS} = w_{SS} - \Delta_1$, $w'_S = w_S + p_1 \Delta_1$, $w'_{FS} = w_{FS} - \Delta_2$, and $w'_F = w_F + (1 - p_1)\Delta_2$. The contract $\vec{w}'$ satisfies the above constraints, $W(\vec{w}', \langle 1\,{}^{1}_{1} \rangle) = W(\vec{w}, \langle 1\,{}^{1}_{1} \rangle)$, and $\vec{w}'$ pays the agent earlier than $\vec{w}$. The incentive compatibility constraints $\text{IC}_{\langle 2\,{}^{2}_{1} \rangle}$ and $\text{IC}_{\langle 0\,{}^{1}_{1} \rangle}$ become

$$(p_1 - p_0) w_S \geq c_1 \qquad (\text{IC}_{\langle 0\,{}^{1}_{1} \rangle})$$

$$(p_1 - E[p_2]) w_S + E[p_2](E[p_2|S,2] - p_1) \frac{c_1}{p_1 - p_0} \geq c_1 - c_2 + E[p_2](c_1 - c_2) \qquad (\text{IC}_{\langle 2\,{}^{2}_{1} \rangle})$$

If $c_2/c_1 \geq \beta_1$ then $\text{IC}_{\langle 0\,{}^{1}_{1} \rangle}$ is binding. Otherwise, $\text{IC}_{\langle 2\,{}^{2}_{1} \rangle}$ is binding. ■

Proof of Proposition 2: The optimal contract $\vec{w}$ that implements action plan $\langle 2\,{}^{2}_{1} \rangle$ satisfies the following incentive compatibility constraints:

$$\begin{aligned}(E[p_2] - E[p_i])(V_S(\vec{w}, \langle 2\,{}^{2}_{1} \rangle) - V_F(\vec{w}, \langle 2\,{}^{2}_{1} \rangle)) \\ + E[p_i](E[p_2|S,2] - E[p_j|S,i])(w_{SS} - w_{SF}) \\ + (1 - E[p_i])(p_1 - E[p_k|F,i])(w_{FS} - w_{FF}) \geq \\ (c_2 + E[p_2]c_2 + (1 - E[p_2])c_1) - (c_i + E[p_i]c_j + (1 - E[p_i])c_k).\end{aligned} \qquad (\text{IC}_{\langle i\,{}^{j}_{k} \rangle})$$

First, I show that $w_S = w_{SF} = w_{FF} = 0$. Suppose $w_S > 0$. Let $\vec{w}'$ be the same as $\vec{w}$ except that $w'_S = 0$, $w'_{SS} = w_{SS} + \frac{w_S}{E[p_2|S,2]} - \epsilon$. There exists an $\epsilon > 0$ such that the contract $\vec{w}'$ satisfies all $\text{IC}_{\langle i\,{}^{j}_{k} \rangle}$ and $W(\vec{w}', \langle 2\,{}^{2}_{1} \rangle) < W(\vec{w}, \langle 2\,{}^{2}_{1} \rangle)$. Now suppose $w_{SF} > 0$. Let the contract $\vec{w}'$ be the same as $\vec{w}$ except that $w'_{SF} = 0$ and $w'_{SS} = w_{SS} + \frac{1 - E[p_2|S,2]}{E[p_2|S,2]} w_{SF} - \epsilon$. There exists an $\epsilon > 0$ such that the contract $\vec{w}'$ satisfies all $\text{IC}_{\langle i\,{}^{j}_{k} \rangle}$ and $W(\vec{w}', \langle 2\,{}^{2}_{1} \rangle) < W(\vec{w}, \langle 2\,{}^{2}_{1} \rangle)$. Finally, suppose $w_{FF} > 0$. If the contract $\vec{w}'$ is the same as $\vec{w}$, except that $w'_{FF} = 0$, and $w'_F = w_F + (1 - p_1) w_{FF}$, then all $\text{IC}_{\langle i\,{}^{j}_{k} \rangle}$ are still satisfied, $W(\vec{w}', \langle 2\,{}^{2}_{1} \rangle) = W(\vec{w}, \langle 2\,{}^{2}_{1} \rangle)$, and the contract $\vec{w}'$ pays the agent earlier than $\vec{w}$.

If follows from $\text{IC}_{\langle 2\,{}^{2}_{0} \rangle}$ and $\text{IC}_{\langle i\,{}^{j}_{1} \rangle}$ that $\text{IC}_{\langle i\,{}^{j}_{0} \rangle}$ and $\text{IC}_{\langle i\,{}^{j}_{2} \rangle}$ are redundant. From $\text{IC}_{\langle 2\,{}^{2}_{0} \rangle}$, we have that $w_{FS} \geq \frac{c_1}{p_1 - p_0}$ and $\text{IC}_{\langle i\,{}^{j}_{1} \rangle}$ implies $\text{IC}_{\langle i\,{}^{j}_{0} \rangle}$. Since $c_2 \geq \frac{E[p_2] - p_0}{p_1 - p_0} c_1$, $\text{IC}_{\langle i\,{}^{j}_{1} \rangle}$ implies $\text{IC}_{\langle i\,{}^{j}_{2} \rangle}$.

Rewriting the incentive compatibility constraints that are not redundant:

$$(p_1 - p_0)(w_{FS} - w_{FF}) \geq c_1 \qquad (\text{IC}_{\langle 2\,{}^{2}_{0} \rangle})$$

$$\begin{aligned}(E[p_2]E[p_2|S,2] - p_1 E[p_j]) w_{SS} + (p_1 - E[p_2]) w_F \\ + ((1 - E[p_2])p_1 - (1 - p_1)p_0) w_{FS} \\ \geq (c_2 + E[p_2]c_2 + (1 - E[p_2])c_1) - (c_1 + p_1 c_j)\end{aligned} \qquad (\text{IC}_{\langle 1\,{}^{j}_{1} \rangle})$$

$$
\begin{aligned}
(E[p_2]E[p_2|S,2] - p_0E[p_j])w_{SS} - (E[p_2]-p_0)w_F \qquad&\\
+ ((1-E[p_2])p_1 - (1-p_0)p_0)w_{FS} \qquad&\\
\geq (c_2 + E[p_2]c_2 + (1-E[p_2])c_1) - p_0c_j \quad& (\mathrm{IC}_{\langle 0\, \substack{j\\1}\rangle})
\end{aligned}
$$

$$
(E[p_2|S,2] - E[p_j])w_{SS} \geq c_2 - c_j. \qquad (\mathrm{IC}_{\langle 2\, \substack{j\\1}\rangle})
$$

The incentive compatibility constraint $\mathrm{IC}_{\langle 2\, \substack{2\\0}\rangle}$ is binding and $w_{FS} = \frac{c_1}{p_1-p_0}$. Suppose $w_{FS} > \frac{c_1}{p_1-p_0}$. If the contract $\vec{w}'$ is the same as $\vec{w}$, except that $w'_{FS} = \frac{c_1}{p_1-p_0}$, and $w'_F = w_F + (1-p_1)(w_{FS} - w'_{FS})$, then all $\mathrm{IC}_{\langle i\, \substack{j\\1}\rangle}$ are still satisfied, $W(\vec{w}', \langle 2\, \substack{2\\1}\rangle) = W(\vec{w}, \langle 2\, \substack{2\\1}\rangle)$, and the contract $\vec{w}'$ pays the agent earlier than $\vec{w}$. On the other hand, the incentive compatibility constraints $\mathrm{IC}_{\langle 1\, \substack{2\\1}\rangle}$, $\mathrm{IC}_{\langle 1\, \substack{0\\1}\rangle}$, $\mathrm{IC}_{\langle 2\, \substack{1\\1}\rangle}$, and $\mathrm{IC}_{\langle 2\, \substack{0\\1}\rangle}$ are redundant. If $c_2 \geq c_1$, $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle}$ implies $\mathrm{IC}_{\langle 1\, \substack{2\\1}\rangle}$, and if $c_2 < c_1$, $\mathrm{IC}_{\langle 1\, \substack{2\\1}\rangle}$ is trivially satisfied. Also, $\mathrm{IC}_{\langle 0\, \substack{1\\1}\rangle}$ and $\mathrm{IC}_{\langle 0\, \substack{1\\2}\rangle}$ imply $\mathrm{IC}_{\langle 1\, \substack{0\\1}\rangle}$. Moreover, $\mathrm{IC}_{\langle 0\, \substack{2\\1}\rangle}$ implies $\mathrm{IC}_{\langle 2\, \substack{0\\1}\rangle}$. Finally, $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle} + \frac{p_1 - E[p_2]}{E[p_2]-p_0}\mathrm{IC}_{\langle 0\, \substack{1\\1}\rangle}$ implies $\mathrm{IC}_{\langle 2\, \substack{1\\1}\rangle}$.

If $c_2/c_1 \geq \beta_2$, then one can show that $w_{SS} \geq \frac{c_1}{p_1-p_0} \geq \frac{c_1-c_2}{p_1-E[p_2]}$. Therefore, $\mathrm{IC}_{\langle 0\, \substack{1\\1}\rangle}$ implies $\mathrm{IC}_{\langle 0\, \substack{0\\1}\rangle}$ and $\mathrm{IC}_{\langle 0\, \substack{2\\1}\rangle}$. Either $w_F > 0$, and $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle}$ and $\mathrm{IC}_{\langle 0\, \substack{1\\1}\rangle}$ are binding or $w_F = 0$ and $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle}$ is binding. When $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle}$ and $\mathrm{IC}_{\langle 0\, \substack{1\\1}\rangle}$ are binding, the contract is always feasible. Comparing the promised wages in each of the two possible contracts one can show that when

$$
\frac{1-E[p_2]}{1-p_1} \geq \frac{E[p_2]E[p_2|S,2]}{p_1^2},
$$

the former contract is less costly for the principal than the latter contract. Otherwise, the latter contract is less costly.

If $c_2/c_1 < \beta_2$, then the candidate for the optimal contract is such that $\mathrm{IC}_{\langle 0\, \substack{j\\1}\rangle}$ and $\mathrm{IC}_{\langle 2\, \substack{2\\0}\rangle}$ are binding, $w_{SS} = w_{SS}^{0j1}$, and $w_F = 0$, where

$$
j \in \arg\max_{\tilde{\jmath}\in\{0,1\}} \quad w_{SS}^{0\tilde{\jmath}1} \equiv \frac{(1+E[p_2])c_2 - p_0c_{\tilde{\jmath}}}{(E[p_2]E[p_2|S,2] - p_0E[p_{\tilde{\jmath}}])} + \frac{(E[p_2]-p_0)p_0\frac{c_1}{p_1-p_0}}{(E[p_2]E[p_2|S,2] - p_0E[p_{\tilde{\jmath}}])}
$$

I first prove that the candidate contract is feasible. For that it suffices to show that $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle}$ is satisfied. If $E[p_2]E[p_2|S,2] \geq p_1^2$, then $\mathrm{IC}_{\langle 0\, \substack{1\\1}\rangle}$ implies $\mathrm{IC}_{\langle 1\, \substack{1\\1}\rangle}$. If $E[p_2]E[p_2|S,2] < p_1^2$,

$$
\begin{aligned}
w_{SS}^{0j1} &< \frac{(1+E[p_2])\beta_2c_1 - p_0c_1}{(E[p_2]E[p_2|S,2] - p_0p_1)} + \frac{(E[p_2]-p_0)p_0\frac{c_1}{p_1-p_0}}{(E[p_2]E[p_2|S,2] - p_0p_1)}\\
&= \frac{(1+E[p_2])\beta_2c_1 - (1+p_1)c_1}{(E[p_2]E[p_2|S,2] - p_1^2)} - \frac{(p_1-E[p_2])p_0\frac{c_1}{p_1-p_0}}{(E[p_2]E[p_2|S,2] - p_0p_1)}\\
&< \frac{(1+E[p_2])c_2 - (1+p_1)c_1}{(E[p_2]E[p_2|S,2] - p_1^2)} - \frac{(p_1-E[p_2])p_0\frac{c_1}{p_1-p_0}}{(E[p_2]E[p_2|S,2] - p_0p_1)}
\end{aligned}
$$

In addition to that, $\mathrm{IC}_{\langle 0\, \substack{j\\1}\rangle}$ is not satisfied for any $w_{SS} < w_{SS}^{0j1}$. Therefore, it is impossible to improve on the candidate contract. ■

Proof of Proposition 3:
The expected payment associated with exploitation is

$$W(\vec{w}_1, \langle {}_{1}{}^{1}_{1} \rangle) = p_1 \left[2\alpha_1 + \frac{c_1(1+E[p_2])}{p_1 - E[p_2]} \left(\beta_1 - \frac{c_2}{c_1} \right)^+ \right],$$

while the expected payment associate with exploration is

$$\begin{aligned} W(\vec{w}_2, \langle {}_{2}{}^{2}_{1} \rangle) &= (1-E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S,2]\alpha_2 \\ &\quad + E[p_2]E[p_2|S,2]\frac{p_1 - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1^2} \left(\frac{c_2}{c_1} - \beta_2 \right)^+ \end{aligned}$$

if exploration is moderate, and

$$\begin{aligned} W(\vec{w}_2, \langle {}_{2}{}^{2}_{1} \rangle) &= (1-E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S,2]\alpha_2 \\ &\quad + E[p_2]E[p_2|S,2]\frac{E[p_2] - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_2 \right)^+ \\ &\quad + (1-E[p_2])\frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_2 \right)^+ . \end{aligned}$$

if exploration is radical. Therefore, the exact payments depend on four conditions:
(1) The value of α_2,
(2) Whether β_1 is greater or less than c_2/c_1, and
(3) Whether β_2 is greater or less than c_2/c_1.
(4) Whether exploration is radical or moderate.

The following definitions will be useful in simplifying the problem:

$$\begin{aligned} \alpha_{20} &= \frac{(1+E[p_2])c_2 + (E[p_2]-p_0)p_0\alpha_1}{E[p_2]E[p_2|S,2] - p_0^2}, \\ \alpha_{21} &= \frac{(1+E[p_2])c_2 - p_0 c_1 + (E[p_2]-p_0)p_0\alpha_1}{E[p_2]E[p_2|S,2] - p_0 p_1}. \end{aligned}$$

Under these definitions, $\alpha_2 = \max\{\alpha_{20}, \alpha_{21}\}$. Then

$$\alpha_{20} - \alpha_{21} = \frac{p_0(c_1 E[p_2](E[p_2|S,2] - p_0) - c_2(p_1 - p_0)(1+E[p_2]))}{(E[p_2]E[p_2|S,2] - p_0^2)(E[p_2]E[p_2|S,2] - p_0 p_1)},$$

so $\alpha_{20} - \alpha_{21} \leq 0$ if

$$c_1 E[p_2](E[p_2|S,2] - p_0) \leq c_2(p_1 - p_0)(1+E[p_2]),$$

or, equivalently,

$$\frac{E[p_2](E[p_2|S,2] - p_0)}{(1+E[p_2])(p_1 - p_0)} \leq \frac{c_2}{c_1}.$$

In other words, $\alpha_2 = \alpha_{21}$ if $\frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2](p_1-p_0))} \leq \frac{c_2}{c_1}$, and $\alpha_2 = \alpha_{20}$ otherwise. It is thus easy to see that

$$\frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)} < \beta_1 < \beta_2.$$

$$\frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)} < \beta_1 < \beta_2.$$

Moreover, one can note that as long as $\beta_2 > \frac{c_2}{c_1}$, $W(\vec{w}_2, \langle {}_2{}^2_1 \rangle)$ does not depend on whether exploration is radical or moderate.

Therefore, depending on how large $\frac{c_2}{c_1}$ is compared to each of the three expressions above and on whether exploration is radical or moderate, the problem can be divided into five cases:

Case Xm. $\frac{c_2}{c_1} \geq \beta_2$, and exploration is moderate,

Case Xr. $\frac{c_2}{c_1} \geq \beta_2$, and exploration is radical,

Case Y1. $\beta_1 \leq \frac{c_2}{c_1} < \beta_2$,

Case Y2. $\frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)} \leq \frac{c_2}{c_1} < \beta_1$, and

Case Y3. $\frac{c_2}{c_1} < \frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)}$.

The expected payment for each case is:

Case Xm. Here $\alpha_2 = \alpha_{21}$, $\beta_1 < \frac{c_2}{c_1}$, $\beta_2 \leq \frac{c_2}{c_1}$, and exploration is moderate.

$$W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) = p_1 \cdot 2\alpha_1,$$

$$\begin{aligned} W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) = {} & (1 - E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S,2]\alpha_{21} \\ & + E[p_2]E[p_2|S,2] \frac{p_1 - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1^2} \left(\frac{c_2}{c_1} - \beta_2\right) \end{aligned}$$

Case Xr. Here $\alpha_2 = \alpha_{21}$, $\beta_1 < \frac{c_2}{c_1}$, $\beta_2 \leq \frac{c_2}{c_1}$, and exploration is radical.

$$\begin{aligned} W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) = {} & (1 - E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S,2]\alpha_{21} \\ & + E[p_2]E[p_2|S,2] \frac{E[p_2] - p_0}{E[p_2]E[p_2|S,2] - p_0 p_1} \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_2\right) \\ & + (1 - E[p_2]) \frac{p_1(1+E[p_2])c_1}{E[p_2]E[p_2|S,2] - p_1 E[p_2]} \left(\frac{c_2}{c_1} - \beta_2\right). \end{aligned}$$

Case Y1. Here $\alpha_2 = \alpha_{21}$, $\beta_1 \leq \frac{c_2}{c_1}$, and $\beta_2 > \frac{c_2}{c_1}$.

$$
\begin{aligned}
W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) &= p_1 \cdot 2\alpha_1, \\
W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) &= (1 - E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S, 2]\alpha_{21}.
\end{aligned}
$$

Case Y2. Here $\alpha_2 = \alpha_{21}$, $\beta_1 > \frac{c_2}{c_1}$, and $\beta_2 > \frac{c_2}{c_1}$.

$$
\begin{aligned}
W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) &= p_1 \left[2\alpha_1 + \frac{c_1(1 + E[p_2])}{(p_1 - E[p_2])}\left(\beta_1 - \frac{c_2}{c_1}\right)\right], \\
W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) &= (1 - E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S, 2]\alpha_{21}.
\end{aligned}
$$

Case Y3. Here $\alpha_2 = \alpha_{20}$, $\beta_1 > \frac{c_2}{c_1}$, and $\beta_2 > \frac{c_2}{c_1}$.

$$
\begin{aligned}
W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) &= p_1 \left[2\alpha_1 + \frac{c_1(1 + E[p_2])}{(p_1 - E[p_2])}\left(\beta_1 - \frac{c_2}{c_1}\right)\right], \\
W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) &= (1 - E[p_2])p_1\alpha_1 + E[p_2]E[p_2|S, 2]\alpha_{20}.
\end{aligned}
$$

With some algebraic simplification, the distortion $(W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) - C(\langle {}_2{}^2_1 \rangle)) - (W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) - C(\langle {}_1{}^1_1 \rangle))$ towards exploration under the five different cases is:

Case Xm.

$$
\frac{p_1(p_1(c_1p_0 + c_2(p_1 - p_0))(1 + p_2) - c_1(1 + p_1)E[p_2]E[p_2|S, 2])}{(p_1 - p_0)(E[p_2]E[p_2|S, 2] - p_1^2)}
$$

Case Xr.

$$
\frac{p_1(c_1p_0 + c_2(p_1 - p_0))(1 + p_2) - c_1(1 + p_1)E[p_2]E[p_2|S, 2]}{(p_1 - p_0)E[p_2](E[p_2|S, 2] - p_1)}
$$

Case Y1.

$$
\frac{p_0(p_1(c_1p_0 + c_2(p_1 - p_0))(1 + p_2) - c_1(1 + p_1)E[p_2]E[p_2|S, 2])}{(p_1 - p_0)(E[p_2]E[p_2|S, 2] - p_0p_1)}
$$

Case Y2.

$$
\frac{E[p_2]}{(p_1 - p_0)(p_1 - E[p_2])(E[p_2]E[p_2|S, 2] - p_0p_1)} * \Big(c_2(p_1 - p_0)p_1(1 + E[p_2])(E[p_2|S, 2] - p_0)
$$
$$
-c_1(p_0^2p_1(1+E[p_2])+p_1E[p_2]E[p_2|S, 2](1+E[p_2|S, 2])-p_0(p_1^2+E[p_2]E[p_2|S, 2]+2p_1E[p_2]E[p_2|S, 2]))\Big)
$$

Case Y3.

$$\frac{E[p_2]}{(p_1-p_0)(p_1-E[p_2])(E[p_2]E[p_2|S,2]-p_0^2)} * \Big(c_2(p_1-p_0)(1+E[p_2])(p_1E[p_2|S,2]-p_0^2)$$
$$-c_1(p_0^3(1+E[p_2])+p_0(1+p_1)E[p_2]E[p_2|S,2]-p_1E[p_2]E[p_2|S,2](1+E[p_2|S,2])+p_0^2(p_1+E[p_2]E[p_2|S,2]))\Big)$$

Each of the above expression increase in $\frac{c_2}{c_1}$. The next step is to find the critical values of c_2/c_1 that make each expression equal to zero. Denote these critical values by γ_{Xm}, γ_{Xr}, γ_{Y1}, γ_{Y2}, and γ_{Y3} for each of the five cases. Solving for the critical values gives:

$$\gamma_{Xm} = \gamma_{Xr} = \gamma_{Y1} = \frac{(1+p_1)E[p_2]E[p_2|S,2]-p_0p_1(1+E[p_2])}{(p_1-p_0)p_1(1+E[p_2])}$$

$$\gamma_{Y2} = \frac{p_0^2p_1(1+E[p_2])+p_1E[p_2]E[p_2|S,2](1+E[p_2|S,2])}{(p_0-p1)p_1(1+E[p_2])(p_0-E[p_2|S,2])}$$

$$-\frac{p_0(p_1^2+E[p_2]E[p_2|S,2]+2p_1E[p_2]sp2)}{(p_0-p1)p_1(1+E[p_2])(p_0-E[p_2|S,2])}$$

$$\gamma_{Y3} = \frac{p_0^3(1+E[p_2])+p_1E[p_2]E[p_2|S,2](1+E[p_2|S,2])}{(p_0-p1)(1+E[p_2])(p_0^2-p_1E[p_2|S,2])}$$
$$\frac{-p_0(1+p_1)E[p_2]E[p_2|S,2]-p_0^2(p_1+E[p_2]E[p_2|S,2])}{(p_0-p1)(1+E[p_2])(p_0^2-p_1E[p_2|S,2])}$$

It is straightforward to check that $\gamma_{Y1}=\beta_2$, $\gamma_{Y2}>\beta_1$, and

$$\gamma_{Y3} > \frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)}.$$

Using these observations, one can reach conclusions about the distortions in each of the five cases:

Cases Xm and Xr. Since $\frac{c_2}{c_1}\geq\beta_2$ and $\beta_2=\gamma_{Y1}$, we also have $\frac{c_2}{c_1}\geq\gamma_{Y1}$, so the principal is biased against exploration.

Case Y1. Since $\frac{c_2}{c_1}<\beta_2$ and $\beta_2=\gamma_{Y1}$, we also have $\frac{c_2}{c_1}<\gamma_{Y1}$, so the principal is biased towards exploration.

Case Y2. Since $\frac{c_2}{c_1} < \beta_1$ and $\beta_1 < \gamma_{Y2}$, we also have $\frac{c_2}{c_1} < \gamma_{Y2}$, so the principal is biased towards exploration.

Case Y3. Since $\frac{c_2}{c_1} < \frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)}$ and $\frac{E[p_2](E[p_2|S,2]-p_0)}{(1+E[p_2])(p_1-p_0)} < \gamma_{Y3}$, we also have $\frac{c_2}{c_1} < \gamma_{Y3}$, so the principal is biased towards exploration. ■

Proof of Proposition 4: Follows from the fact that $\text{IC}_{\langle 1\,{}^{0}_{1}\rangle}$ and $\text{IC}_{\langle 1\,{}^{1}_{0}\rangle}$ are binding under the optimal long-term contract. ■

Proof of Proposition 5: In order to implement $\langle 2\,{}^{2}_{1}\rangle$, the following incentive compatibility constraints must be satisfied:

$$\begin{aligned}(E[p_2]-E[p_i])(V_S(\vec{w},\langle 2\,{}^{2}_{1}\rangle)-V_F(\vec{w},\langle 2\,{}^{2}_{1}\rangle))+E[p_i](E[p_2|S,2]-E[p_j|S,i])(w_{SS}-w_{SF})\\ +(1-E[p_i])(p_1-E[p_k|F,i])(w_{FS}-w_{FF})\geq\\ (c_2+E[p_2]c_2+(1-E[p_2])c_1)-(c_i+E[p_i]c_j+(1-E[p_i])c_k).\quad (\text{IC}_{\langle i\,{}^{j}_{k}\rangle})\end{aligned}$$

Moreover, for the contract to be renegotiation-proof, we must have $j,k \in \mathcal{I}$ such that $\text{IC}_{\langle 2\,{}^{j}_{1}\rangle}$ and $\text{IC}_{\langle 2\,{}^{2}_{k}\rangle}$ bind.

If $c_2 \geq \frac{E[p_2|S,2]-p_0}{p_1-p_0}c_1$, from $\text{IC}_{\langle 2\,{}^{1}_{1}\rangle}$ we have that

$$w_{SS} = \frac{c_2-c_1}{E[p_2|S,2]-p_1}$$

$$w_{SF} = 0.$$

This contradicts $\text{IC}_{\langle 1\,{}^{1}_{1}\rangle} + \frac{p_1-E[p_2]}{E[p_2]-p_0}\text{IC}_{\langle 0\,{}^{1}_{1}\rangle}$. Therefore, $\langle 2\,{}^{2}_{1}\rangle$ is not implementable with a sequence of short-term contracts if $c_2 \geq \frac{E[p_2|S,2]-p_0}{p_1-p_0}c_1$. If $c_2 < \frac{E[p_2|S,2]-p_0}{p_1-p_0}c_1$, from $\text{IC}_{\langle 2\,{}^{0}_{1}\rangle}$ we have that

$$w_{SS} = \frac{c_2}{E[p_2|S,2]-p_0}$$

$$w_{SF} = 0.$$

From $\text{IC}_{\langle 2\,{}^{2}_{k}\rangle}, k \in \{0,2\}$ we have that

$$w_{FS} = \frac{c_1}{p_1-p_0}$$

$$w_{FF} = 0$$

Using the above equations we can rewrite the following incentive compatibility constraints:

$$w_S \geq \frac{c_2(1-p_0)}{E[p_2]-p_0} + p_0\frac{c_1}{p_1-p_0} \qquad (\text{IC}_{\langle 0\,{}^{2}_{1}\rangle})$$

$$w_S \geq \frac{c_2(E[p_2|S,2] - p_0(1 - (p_1 - E[p_2])))}{(E[p_2|S,2] - p_0)(E[p_2] - p_0)} - \frac{c_1 p_0(E[p_2|S,2] - p_0)}{(E[p_2|S,2] - p_0)(E[p_2] - p_0)} + p_0 \frac{c_1}{p_1 - p_0} \quad (\text{IC}_{\langle {}_0{}^1_1 \rangle})$$

$$w_S \geq \frac{c_2(E[p_2|S,2] - p_0(1 + E[p_2]) + p_0^2)}{(E[p_2|S,2] - p_0)(E[p_2] - p_0)} + p_0 \frac{c_1}{p_1 - p_0} \quad (\text{IC}_{\langle {}_0{}^0_k \rangle})$$

It is easy to show that, given $c_2 < \frac{E[p_2|S,2]-p_0}{p_1-p_0} c_1$, $\text{IC}_{\langle {}_0{}^0_1 \rangle}$ implies $\text{IC}_{\langle {}_0{}^1_1 \rangle}$ and $\text{IC}_{\langle {}_0{}^2_1 \rangle}$. Therefore, from $\text{IC}_{\langle {}_0{}^0_1 \rangle}$, our candidate for w_S is

$$w_S = \frac{c_2}{E[p_2] - p_0} - \frac{p_0 c_2}{E[p_2|S,2] - p_0} + p_0 \frac{c_1}{p_1 - p_0}$$

It can be shown that the candidate contract satisfies all other incentive compatibility constraints if and only if

$$c_2 < \frac{(E[p_2|S,2] - p_0)(1 + p_1)}{(p_1 - p_0)(\frac{E[p_2|S,2]-p_0}{E[p_2]-p_0} + p_1)} c_1$$

In this case, the sequence of short-term contracts derived above is the optimal sequence of short-term contracts. ■

Proof of Proposition 6: Similar to the proof of Proposition 1. ■

Proof of Corollary 1: Comparing the costs of implementing exploitation and exploitation with termination from the contracts derived in Propositions 1 and 6, one obtains that: $W(\vec{w}_1, \langle {}_1{}^1_1 \rangle) - W(\vec{w}_6, \langle {}_1{}^1_t \rangle) = (1 - p_1 + p_0)p_1\alpha_1 > (1 - p_1)p_1\alpha_1$. There is inefficient termination with exploitation. ■

Proof of Proposition 7: Similar to the proof of Proposition 2. ■

Proof of Corollary 2: Follows from comparing the costs of implementing exploration and exploration with termination from the contracts derived in Propositions 2 and 7. If $c_2/c_1 > \max(\kappa_m, \kappa_e)\beta_2 + (1 - \max(\kappa_m, \kappa_e))\beta_7$, then $W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) - W(\vec{w}_7, \langle {}_2{}^2_t \rangle) > (1 - E[p_2])p_1\alpha_2$ and there is inefficient continuation with exploration. If $c_2/c_1 < \max(\kappa_m, \kappa_e)\beta_2 + (1 - \max(\kappa_m, \kappa_e))\beta_7$, then $W(\vec{w}_2, \langle {}_2{}^2_1 \rangle) - W(\vec{w}_7, \langle {}_2{}^2_t \rangle) < (1 - E[p_2])p_1\alpha_2$ and there is inefficient termination with exploration. ■

Proof of Proposition 8: For the no feedback policy to have any effect the principal must set $w_S = w_F$, or otherwise the agent can infer the output in the first period from the first period wages. Therefore, the optimal contract $\vec{w}$ that implements action plan $\langle {}_1{}^1_1 \rangle$ without feedback must have $w_S = w_F$ and satisfy the following incentive compatibility constraints:

$$\begin{aligned}(p_1 - E[p_i])(V_S(\vec{w}, \langle 1\,{}^{1}_{1}\rangle) - V_F(\vec{w}, \langle 1\,{}^{1}_{1}\rangle))& \\ + E[p_i](p_1 - E[p_j|S,i])(w_{SS} - w_{SF})& \\ + (1 - E[p_i])(p_1 - E[p_k|F,i])(w_{FS} - w_{FF}) \geq& \\ (c_1 + p_1 c_1 + (1-p_1)c_1) - (c_i + E[p_i]c_j + (1 - E[p_i])c_k)& \quad (\text{IC}_{\langle i\,{}^{j}_{k}\rangle})\end{aligned}$$

for all $\langle i\,{}^{j}_{k}\rangle \neq \langle 1\,{}^{1}_{1}\rangle$ with $j = k$.

First, I show that $w_S = w_F = 0$. Suppose $w_S = w_F > 0$. A contract $\vec{w}'$ that is the same as $\vec{w}$ but has $w_S = w_F = 0$ satisfies all the above constraints and has $W(\vec{w}', \langle 1\,{}^{1}_{1}\rangle) < W(\vec{w}, \langle 1\,{}^{1}_{1}\rangle)$. Next, I show that $w_{FF} = 0$. Suppose that $w_{FF} > 0$. A contract $\vec{w}'$ that is the same as $\vec{w}$ but has $w_{FF} = 0$ satisfies all the above constraints and has $W(\vec{w}', \langle 1\,{}^{1}_{1}\rangle) < W(\vec{w}, \langle 1\,{}^{1}_{1}\rangle)$.

Since $c_2/c_1 \geq (E[p_2] - p_0)/(p_1 - p_0)$, $\text{IC}_{\langle 0\,{}^{1}_{1}\rangle}$ and $\text{IC}_{\langle 0\,{}^{0}_{0}\rangle}$ imply $\text{IC}_{\langle 0\,{}^{2}_{2}\rangle}$. Similar arguments can be used to show that $\text{IC}_{\langle 2\,{}^{1}_{1}\rangle}$, $\text{IC}_{\langle 1\,{}^{2}_{2}\rangle}$ and $\text{IC}_{\langle 2\,{}^{0}_{0}\rangle}$ are redundant.

The remaining incentive compatibility constraints can be written as

$$\begin{aligned}(p_1^2 - p_0^2)w_{SS} + (p_1(1-p_1) - p_0(1-p_0))w_{SF}& \\ + (p_1(1-p_1) - p_0(1-p_0))w_{FS} \geq 2c_1& \quad (\text{IC}_{\langle 0\,{}^{0}_{0}\rangle})\end{aligned}$$

$$\begin{aligned}(p_1^2 - E[p_2]E[p_2|S,2])w_{SS} + (p_1(1-p_1) - E[p_2](1 - E[p_2|S,2]))w_{SF}& \\ + (p_1(1-p_1) - (1 - E[p_2])E[p_2|F,2])w_{FS} \geq 2(c_1 - c_2)& \quad (\text{IC}_{\langle 2\,{}^{2}_{2}\rangle})\end{aligned}$$

$$(p_1^2 - p_0 p_1)w_{SS} + (1-p_1)(p_1 - p_0)w_{SF} - p_1(p_1 - p_0)w_{FS} \geq c_1 \qquad (\text{IC}_{\langle 0\,{}^{1}_{1}\rangle})$$

$$(p_1^2 - p_0 p_1)w_{SS} - p_1(p_1 - p_0)w_{SF} + (1-p_1)(p_1 - p_0)w_{FS} \geq c_1 \qquad (\text{IC}_{\langle 1\,{}^{0}_{0}\rangle})$$

Using Bayes' rule the incentive compatibility constraint $\text{IC}_{\langle 2\,{}^{2}_{2}\rangle}$ can be written as

$$\begin{aligned}(p_1^2 - E[p_2]E[p_2|S,2])w_{SS} + (p_1(1-p_1) - E[p_2](1 - E[p_2|S,2]))w_{SF}& \\ + (p_1(1-p_1) - E[p_2](1 - E[p_2|S,2]))w_{FS} \geq 2(c_1 - c_2)& \quad (\text{IC}_{\langle 2\,{}^{2}_{2}\rangle})\end{aligned}$$

I now show that we can restrict attention to contracts that have $w_{SF} = w_{FS}$. Suppose $w_{SF} \neq w_{FS}$. Therefore, a contract $\vec{w}'$ that has $w'_{SF} = w'_{FS} = (w_{SF} + w_{FS})/2$ satisfies all of the above incentive compatibility constraints and has $W(\vec{w}, \langle 1\,{}^{1}_{1}\rangle) = W(\vec{w}', \langle 1\,{}^{1}_{1}\rangle)$.

The candidate for the optimal contract is the one in the statement of Proposition 8. If $c_2/c_1 \geq \beta_8$ then only $\mathrm{IC}_{\langle 0\,{}^{0}_{0}\rangle}$ is binding. If $c_2/c_1 < \beta_8$, then both $\mathrm{IC}_{\langle 0\,{}^{0}_{0}\rangle}$ and $\mathrm{IC}_{\langle 2\,{}^{2}_{2}\rangle}$ are binding. One can check that $\mathrm{IC}_{\langle 1\,{}^{0}_{0}\rangle}$ and $\mathrm{IC}_{\langle 0\,{}^{1}_{1}\rangle}$ are satisfied under the optimal contract. ■

Proof of Proposition 9: Action plan $\langle 2\,{}^{2}_{1}\rangle$ can only be implemented if the principal provides feedback on performance to the agent. ■

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