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Principal-Multiagent Relationships with Costly Monitoring

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Abstract

This paper analyses the principal and multi-agent relationships with costly monitoring. When monitoring is costly, the choice of monitoring is a strategic variable. Randomization of actions induces the incentive for monitoring and the principal can extract a relevant information about actions from agents by communicating with the agents. If monirorint cost is sufficiently small, then first-best outcomes are approximately implementable. Moreover, under certain conditions, we construct a contract to approximately implement the desired action profile as a unique sequential equilibrium with first-best outcome.

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1. Introduction

Monitoring is one of the important activities in various organizations. To know what is going on in the organization can improve the efficiency of production. For example, job rotation is applied in many Japanese firms. It enables the workers to know what their colleagues are doing. Managers often delegate monitoring activity to workers.

In the present paper, we consider the costly monitoring situation. The principal (manager) can not monitor the agents, but each agent (worker) can perfectly monitor the opponent if he pays a cost. If he does not pay a cost, he can not obtain any information about the opponent. And, we assume that monitoring is private. Each agent can not know whether he is monitored by the opponent and his observed information is private. This situation has not been analysed. In our costly monitoring situation, since the principal is assumed not to enforce the agents to monitor each other, the principal needs to design the incentive contracts while she consider additional incentive constraint that agents voluntarily monitor the opponent's action.

In the literature on principal and many agents relationships, several papers have studied the situation where agents take unobservable actions and have characterized the optimal incentive contracts. And it has become apparent that, in many situations, the first-best outcome is not attainable. The second-best outcome is attainable, that is, efficiency losses arise. See Holmström (1982) and Mookherjee (1984). On the other hand, when agents can perfectly observe opponents' actions at no coste, it has been shown that efficiency losses can be improved: Ma (1988) and Itoh (1993). In particular, Ma (1988) has shown that the first-best result can be established when each agent (worker) can monitor the opponents' actions at no cost and communication is available. In his analysis, costless mointoring is crucial.

Our model relaxes the perfect monitoring assumption in Ma (1988) and Itoh (1993). The present paper closely relates to Ma (1988) in that, though the agent has to pay a cost, each agent can perfectly monitor the opponent and communication is possible.[1] There are two distinctions between Ma (1988) and ours. One of them is with regard to monitoring technologies as stated above. The other is with regard to the timing of communication. We assume the simultaneous communication that each agent simultaneously announces a message. Moreover, we focus on a simple communication that each agent uses only two messages. The principal has only to know whether her desired actions are chosen or not, in order to (virtually) implement an action profile. On the othere hand, Ma (1988) uses sequential communication that agent 2 announces a message after knowing agent 1's announced message. Though sequantial communication is often useful for unique implementaion, we do not have to rely on it.

Our question is whether (approximate) first-best outcome is attainable in the costly monitoring situation. It is shown that there exists no contract that *exactly* implements the first-best action at less than the second-best cost. In other words, only the second-best outcome is attainable, even if communication is possible, when we focus on is a contract under which the first-best action is chosen with probability one in equilibrium. That is shown in section 3.

However, if we permit the agents to randomize their actions, approximate first-best outcome is attainable when monitoring costs are sufficiently small. Approximate first-best outcome means that the first-best action profile is chosen with almost probability one and the expected implementation cost is almost the first-best. And, we say that the first-best action profile is *virtually* implementable if there exists a contract under which the first-best action profile is chosen with almost probability one in equilibrium. In the costly monitoring situation, randomization of actions is necessary to give each agent incentive to monitor the opponent. In the perfect monitoring situation, agents do not have to randomize actions since it is not needed to consider incentive for monitoring.

[1] Itoh (1993) assumes that the principal can not communicate with the agents. He shows that the principal can implement any action profile with less costs under agent side contracting than under no side contract. However, in his setting, first-best outcome is not attainable.

We can show that the first-best action profile is not only virtually but also uniquely implementable at alomost the same cost as the first-best. Firstly, as the benchmark, we provide a contract that induces approximate first-best outcome, where the agents' wages are not contingent on public output but only on messages. Then, it will be apparent that, given the contract, the agents do not choose the principal's preferred equilibrium. The agents may choose a bad equilibrium for the principal but it is Pareto superior equilibrium in the agent's view point. Next, we consider wages contigent on output as well as messages, and for the first step for unique implementability, we provide a contract that induces an approximate first-best outcome and have its equilibrium which Pareto-dominates any other equilibrium. Lastly, under certain conditions, we present a contract which induces a unique sequential equilibrium with approximate first-best outcome.

The paper proceeds as follows. In section 2, we set up the model. In section 3, we discuss a contract which virtually implements first-best actions when monitoring is costly and the wages are not contingent on outputs but messages. Section 4 presents a contract under which first-best action profile is virtually implementable in coalition-proof Nash equilibrium. In section 5, we introduce a contract that uniquely and virtually implements first-best action profile in sequential equilibrium.

2. The Model

We consider a principal and two agents model with the following timing[2]:

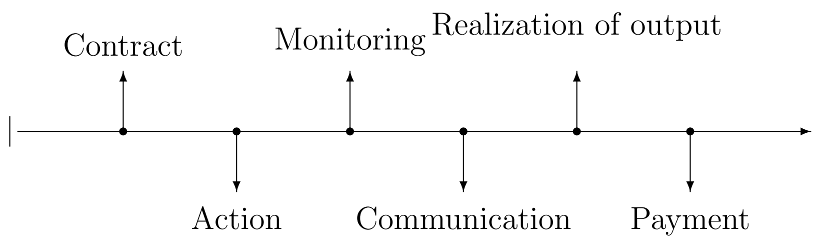

Figure 1. Timing

[2]Although, in the present paper, two agents case is analised, some modification induces the same results in the case of more than two agents.

In the *contract* stage, the principal offers the agents an incentive contract. If any agent rejects the offer, the game ends and all parties receive their reservation utility levels. Without loss of generality, we normalize each agent's reservation utility level to be zero. If both of the agents accept the contract, the game goes to the next stage. The contract specifies the wage schedule, s_k, and the set of messages, M_k, available to agent k. Agent k's wage is contingent on verifiable variables. Hence, contracts are represented by $\{s_k(\cdot), M_k\}_{k=1,2}$.

In the *action* stage, each agent simultaneously chooses an effort level, a_k, from the finite set A_k. The set, A_1 (resp. A_2), has I (resp. J) elements. That is, $A_1 = \{a_1^1, \cdots, a_1^I\}$ (resp. $A_2 = \{a_2^1, \cdots, a_2^J\}$). Agent k's behavioral strategy in the action stage is to choose probability distribution over A_k. That is, we allow agents to mix actions. Denote $\pi_k \in \Delta(A_k)$ as agent k's mixed action, where $\Delta(A_k)$ is the set of the probability distributions over A_k.

In the *monitoring* stage, each agent can privately monitor the opponent's action before the output is realized. The set of choice in monitoring stage is denoted by $G = \{\gamma, \phi\}$, where γ denotes monitoring and ϕ denotes no monitoring. The monitoring strategy is defined by the mapping $g_k : A_k \to \Delta G$, where ΔG is the set of probability distributions over G. To monitor the opponent costs γ (> 0).[3] In the following discussion, we focus on the situation where γ is sufficiently small. If agent k monitors the opponent, he knows perfectly which action the opponent has chosen. However, whether he has monitored or not can not be known by anyone else. For example, when agent 1 chooses effort level a_1^i, he monitors the opponent, and observes a_2^j, then $(a_1^i; a_2^j)$ is private information. If agent k does not monitor the opponent, he can not obtain any additional information at all. Then $(a_k; \phi)$ is his private information.

$(a_k; a_{-k})$ and $(a_k; \phi)$ are said to be agent k's state. We denote agent k's state by $\hat{\omega}_k$. It is the information he obtains before communication stage. The set of agent k's state is denoted by $\hat{\Omega}_k \equiv A_k \times \Omega_k$, where $\Omega_k \equiv A_{-k} \cup \{\phi\}$. Before the communication stage,

[3]Though we denote γ both the decision of monitoring and monitoring cost, that will be not confusing.

agent k observes the $\omega_k \in \Omega_k \equiv A_{-k} \cup \{\phi\}$, and $(a_k; \omega_k)$ is his private information, i.e. his state.

In the *communication* stage, each agent simultaneously and publicly announces a message, m_k, from the finite set M_k, which is specified in the accepted contract. In the following analysis, we can induce the desirable results by restricting the messages available to each agent to R and P, i.e., $M_k = \{R, P\}$ for all $k = 1, 2$. The reporting strategy f_k for agent k is defined by the mapping from agent k's state to the set of his messages. That is, $f_k : \hat{\Omega}_k \to \Delta(M_k)$, where $\Delta(M_k)$ is the set of probability distributions over M_k.

Finally, in the *payment* stage, the principal pay the agents the wages $\{s_k\}_{k=1,2}$ according to the accepted contract when the output $x \in X$ realizes. X is the set of possible outputs. The probability distribution of output x conditional on action pair (a_1, a_2) is denoted by $p(x|a_1, a_2)$. We assume that this distribution has *full support*, that is, for each $(a_1, a_2) \in A_1 \times A_2$ and each $x \in X$, $p(x|a_1, a_2) > 0$. x could be multi-dimensional. Assume that the number of possible realizations of x is L, that is, $|X| = L$. We assume that realized output is publicly observable (to the principal and all the agents) and verifiable (to court).

Each agent's utility is a additively separable with respect to wage, action, and monitoring: $u_k(s_k) - C_k(a_k) - \gamma_k$. $u_k(\cdot)$ is the agent k's utility of wage. $C_k(a_k)$ represents the disutility, or cost, of taking action a_k. Agent 1's disutility function $C_1(\cdot)$ is strictly increasing, that is, $C_1(a_1^i)$ is strictly in i. And assume $C_1(a_1^i) > 0$ for each $i \in \{1, \ldots, I\}$. Similarly, $C_2(a_2^j)$ is increasing in j and $C_2(a_2^j) > 0$ for each $j \in \{1, \ldots, J\}$. γ_k is monitoring cost. If agent k monitors the opponent, then $\gamma_k = \gamma$. Otherwise, $\gamma_k = 0$.

We assume that each agent is risk averse. That is, $u_k(\cdot)$ is continuous, strictly increasing, concave, and unbounded. Note that these assumptions imply that the inverse function $h_k(\cdot) = u_k^{-1}(\cdot)$ exists and that, for any $v \in \mathscr{R}$, there exists $s \in \mathscr{R}$ such that $u_k(s) = v$.

Agent k's wage s_k is paid contingent on verifiable variables. Here, output x and publicly announced message pair (m_1, m_2) are verifiable. Hence, the wage is a function of x and $m = (m_1, m_2)$, that is, $s_k(x, m)$ is paid to agent k when x and m is realized.

A strategy of agent k is defined by $\sigma_k = (\pi_k, g_k, f_k)$. Given strategy $\sigma = (\sigma_1, \sigma_2)$, agent k's expected utility is defined by

$$U_k(\sigma) = E\left[u_k(s_k(x, m)) - C_k(a_k) \mid \sigma\ \right].$$

The principal is risk neutral with utility function $V(x) - \sum_{k=1,2} s_k$, where $V(x)$ is the principal's private benefit from output x. And the principal's expected utility is defined by

$$B(\sigma) = E\left[\sum_{x \in X} p(x|a)\left\{V(x) - \sum_{k=1,2} s_k(x, m)\right\} \Bigm| \sigma\ \right].$$

In the first-best situation where the agents' actions are observable and verifiable, the principal can force the agents to choose any action pair (a_1, a_2) by guaranteeing exactly their resevation utilities. Then, the minimum cost to induce a_k is $h_k(C_k(a_k))$. The first-best action pair is the one that maximizes the principal's expected utility

$$E\left[\sum_{x \in X} p(x|a)V(x)\right] - \sum_{k=1,2} h_k(C_k(a_k)).$$

And, we donote it by $a^e = (a_1^e, a_2^e)$. The first-best outcome is the one in which the principal implements action pair a^e at the first-best cost $h_1(C_1(a_1^e)) + h_2(C_2(a_2^e))$. We impose an assumption for non-trivial situation.

Assumption 1: There exists unique (a_1^e, a_2^e) that satisfies $C_k(a_k^e) > C_k(a_k^1)$ for each $k = 1, 2$.

In the second-best situation, that is, each agent can not observe the opponent and communication is not possible, wages paid to agents are contingent only on outcomes. A contract $\{s_k(\cdot)\}_{k=1,2}$ implements a^e without communication if and only if it satisfies the incentive compatibility and individual rationality

$$\sum_{x\in X} p(x|a^e)u_k(s_k(x)) - C_k(a_k^e) \geq \sum_{x\in X} p(x|a_k^i, a_{-k}^e)u_k(s_k(x)) - C_k(a_k^i), \quad \forall i, \text{ and } \forall k = 1, 2,$$

and

$$\sum_{x\in X} p(x|a^e)u_k(s_k(x)) - C_k(a_k^e) \geq 0, \quad \forall k = 1, 2.$$

The second-best cost to induce a^e is denoted by $h_1^{SB}(a^e) + h_2^{SB}(a^e)$, which is equal to

$$h_1^{SB}(a^e) + h_2^{SB}(a^e) = \min_{s_1(\cdot), s_2(\cdot)} \sum_{x\in X} p(x|a^e)h_1(u_1(s_1(x))) + \sum_{x\in X} p(x|a^e)h_2(u_2(s_2(x))).$$

Under assumption 1 and risk-averse agents, it holds that $h_1^{SB}(a^e)+h_2^{SB}(a^e) > h_1(C_1(a_1^e))+h_2(C_2(a_2^e))$. In the second-best situation, it is possible that a^e is never implementable.

3. Benchmark

Ma (1988) analyzes the perfect monitoring siutation, which are closely related to ours. In his model, each agent can perfectly observe the opponents' action at no cost, and the principal can not do at all. Then, there exists a contract to implement the first-best action pair at the first-best cost. Consider the following contract in which wages are contingent only on messages. If agent 1 announces message R, then agent 2 is paid $h_2(C_2(a_2^e))$. If agent 1 announces P, agent 2 is paid d, where $d < h_2(C_2(a_2^1))$. Payments to agent 1 are analogously defined. Then, it is easy to show that strategy of choosing a_k^e with probability one and announcing R if the oppnents chooses a_{-k}^e and P otherwise forms a perfect equilibrium.

The above contract exhibits the unsatisfactory aspect that a bad equilibrium for the principal exists. That is, strategy of choosing a_k^1 and announcing always R also constitute a perfect equilibrium. In order to solve that problem, Ma (1988) introduced a sequential message reporting communication. And, he showed that when wages are contingent on output as well as messages, under a certain condition, there exists a contract that uniquely implements the first-best action pair at the first-best cost in subgame perfect equilibrium.

There is a prominent distinction between the perfect and costly monitoring situation. In the perfect monitoring situation, there exists a contract to implement the first-best action pair as an equilibrium in which the first-best action pair is chosen probability one, in other words, it is *exactly* implementable at the first-best cost. However, in the costly monitoring, there exists no contract under which the first-best action pair is exactly implemented at even near first-best cost. We provides the following proposition.

Proposition 1: For any positive γ, if the first-best action pair is exactly implementable, then its implementation cost is the second-best one.

Suppose that there exists a contract such that (a_1^e, a_2^e) is chosen with probability one in equilibrium. Then, each agent does not monitor the opponent. Since, on the equilibrium path, agent k believes that the opponent chooses a_{-k}^e with probability one, he can knows which action has chosen without monitoring the opponent. Hence, to monitor the opponent is not a best response for each agent. Therefore, if (a_1^e, a_2^e) is surely chosen on the equilibirum path, agent k reaches the state $(a_k^e; \phi)$ with probability one. That is, if agent unilaterally deviated from the first-best action, he could not be detected by the opponent. The message reported by agent is not valuable since it does not convey additional information his opponent's at all. The discussion implies that contract which exactly implement a^e is, essentially, one without communication. Consequently, if a^e is exactly implementable, the implementation cost is the second-best one.

In the present paper, we allow agents to mix actions and focus on the situation where monitoring cost γ is sufficiently small. And, We examine whether it is possible that, in the equilibrium, the first-best action pair is chosen with high probability and the expected payment to the agents is approximately equal to the first-best cost.

Definition 1: We say that $\hat{a}$ is virtually implementable if, for any positive δ, there exists $\gamma(> 0)$ and a contract under which there is an equilibirum strategy $\{(\pi_k, g_k, f_k)\}_{k=1,2}$ such that $|\pi_k - \hat{\pi}_k| < \delta$ for $k = 1, 2$, where $\hat{\pi}_k$ is the vector such that $\hat{\pi}_k(\hat{a}_k) = 1$ and $\hat{\pi}_k(a_k) = 0$

for all $a_k \neq \hat{a}_k$.[4]

Assume that the wages are not contingent on outputs but only on messages. From the discussion on proposition 1, if the wages are not contingent on outputs, the first-best action pair is never exactly implementable. On the other hand, the first-best action pair is virtually implementable with almost the same costs as in the first-best situation. Consider the contract in which there are two available messages for each agent and wages are contingent only on messages. It is summarized by table 1.

	R	P
R	$C_1^e + \alpha_1,\ C_2^e + \alpha_2$	$0,\ \underline{C}_2$
P	$\underline{C}_1,\ 0$	$\underline{C}_1,\ \underline{C}_2$

Table 1.

Hereafter, we use the corresponding utility payment instead of explicit monetary payment. In each cell, agents' utility payments are written. For example, agent 1's utility payments are $v_1(R,R) = u_1(s_1(R,R)) = C_1(a_1^e)+\alpha_1 = C_1^e+\alpha_1$, $v_1(P,P) = u_1(s_1(P,P)) = C_1(a_1^1) = \underline{C}_1$, and $v_1(R,P) = u_1(s_1(R,P)) = 0$.

Given the above contract, there is a following type of equilibrium strategy $\hat{\sigma} = (\hat{\sigma}_1, \hat{\sigma}_2)$.

$$\hat{\sigma}_k:\ \hat{\pi}_k(a_k) = \begin{cases} 1-\delta_k(\gamma) \text{ if } a_k = a_k^e \\ \\ \delta_k(\gamma) \quad \text{if } a_k = a_k^1 \end{cases},\quad \hat{g}_k(a_k) = \begin{cases} \gamma \text{ if } a_k = a_k^e \\ \\ \phi \text{ otherwise} \end{cases},$$

$$\hat{f}_k(\hat{\omega}_k) = \begin{cases} R \ \text{ if } \hat{\omega}_k = (a_k^e; a_{-k}^e), (a_k^e; \phi) \\ \\ P \qquad \text{otherwise} \end{cases}.$$

$\delta_k(\gamma)$ will be defined below.

[4] $|\cdot|$ represents the standard Euclidian norm.

Following this strategy, agent k mixes between a_k^e and a_k^1. If he chooses a_k^e, then he monitors the opponent, and otherwise, he does not. And only if his state is $(a_k^e; a_{-k}^e)$ and $(a_k^e; \phi)$, then he announces R, and otherwise, P.

Proposition 2: Suppose that wages are contingent only on announced messages. Then, there exists a contract that virtually implements (a_1^e, a_2^e) with almost the same cost as in the first-best.

Proof: We show that $\hat{\sigma}$ is a sequential equilibrium strategy. Since the discussions are same for each agent, we show that the above strategy is a best response for agent 1 given $\hat{\sigma}_2$. First, show that if each agent follows the equilibirum strategy, agent 1 has an incentive to mix between a_1^e and a_1^1, that is, he is indifferent between a_1^e and a_1^1.

$$(1-\delta_2(\gamma)) \cdot (C_1^e + \alpha_1) + \delta_2(\gamma) \cdot \underline{C}_1 - C_1^e - \gamma = \underline{C}_1 - \underline{C}_1 = 0.$$

The first equality implies that a_1^e and a_1^1 are indifferent and the second equality implies that the reservation utility is guaranteed in the equilibrium. Arranging the above equation yields

$$\delta_2(\gamma) = \frac{\alpha_1 - \gamma}{\Delta_1^e + \alpha_1},$$

where $\Delta_1^e = C_1^e - \underline{C}_1$.

Define that α_1 is a function of γ as following.

$$\alpha_1(\gamma) = \gamma^\kappa, \quad \text{where} \;\; 0 < \kappa < 1.$$

Hence,

$$\delta_2(\gamma) = \gamma^\kappa \frac{1-\gamma^{1-\kappa}}{\Delta_1 + \gamma^\kappa} = \gamma^\kappa \cdot D_1(\gamma).$$

When $0 < \gamma \leq \bar{\gamma}$, it is satisfied that $0 < D(\bar{\gamma}) \leq D_1(\gamma) < 1/\Delta_1$. Then, $\delta_2(\gamma) > 0$ is satisfied for any γ such that $0 < \gamma < \bar{\gamma}$.

If each agent follows the equilibrium strategy, to choose a_1^i such that $i \neq 1, e$ is not a best response since agent 1's expected utility is $\underline{C}_1 - C_1(a_1^i) < 0$. Therefore, it has been shown that, for any γ $(0 < \gamma < \bar{\gamma})$, $\hat{\pi}_1$ is a best response. Then, $\lim_{\gamma \to 0} \alpha_1(\gamma) = 0$, and $\lim_{\gamma \to 0} \delta_2(\gamma) = 0$. That is, $\hat{\pi}_2(a_2^e)$ tends to one as γ goes down to zero. And these implies that the implementation cost tends to the first-best one.

Secondly, the incentive in the monitoring stage is examined. Agent 1's future expected utility after choosing a_1^e is, when he monitors,

$$\hat{E}_1^{\gamma} = (1 - \delta_2(\gamma)) \cdot (C_1^e + \alpha_1) + \delta_2(\gamma) \cdot \underline{C}_1 - \gamma.$$

When he does not monitor, he will obtain at most

$$\hat{E}_1^{\phi} = (1 - \delta_2(\gamma)) \cdot (C_1^e + \alpha_1).$$

Then, for sufficiently small γ, it is satisfied that

$$\hat{E}_1^{\gamma} - \hat{E}_1^{\phi} = \gamma^{\kappa}(\underline{C}_1 \cdot D_1(\gamma) - \gamma^{1-\kappa}) > 0.$$

Thus, when agent 1 chose a_1^e, to monitor the opponent's action is a best response. That is, $\hat{g}_1(a_1^e) = \gamma$. On the other hand, after choosing a_1^i such that $i \neq e$, when he dose not monitor, his expected utility is $\underline{C}_1$, and when he does, $\underline{C}_1 - \gamma$. Hence, when choosing a_1^e, not monitoring is a best response. That is, $\hat{g}_k(a_1^i) = \phi$ for all $i \neq e$.

Finally, the best responses in the communication stage are examined. Define that $\mu_1(\hat{\omega}_1\ ; \hat{\sigma})(R)$ is the belief of agent 1 induced according to the equilibrium strategy $\hat{\sigma}$. That is, it is agent 1's belief at state $\hat{\omega}_1$ that agent 2 would announce R. The belief at each state is as follows.

$$\mu_1((a_1^e; a_2^e)\ ; \hat{\sigma})(R) = 1, \tag{1}$$

$$\mu_1((a_1^e; \phi)\ ; \hat{\sigma})(R) = 1 - \delta_2(\gamma), \tag{2}$$

$$\mu_1(\hat{\omega}_1\ ; \hat{\sigma})(R) = 0, \quad \forall \hat{\omega}_1 \neq (a_1^e; a_2^e), (a_1^e; \phi) \tag{3}$$

From (1), at state $(a_1^e; a_2^e)$, agent 1 believes that agent 2 would announce R. Then, R is a strict best response for agent 1. From (2), at state $(a_1^e; \phi)$, agent 1 believes that agent 2 would announce R with almost probability one when γ is sufficiently small. Then, R is a strict best response for agent 1. From (3), at each state other than $(a_1^e; a_2^e)$, agent 1 believes that agent 2 would announce P. Then, P is a strict best response for agent 1.

The above discusstions are true to agent 2. **Q.E.D.**

Although the above contract viutually implements (a_1^e, a_2^e), the unsatisfactory aspect of the contract is that there exists a bad equilibrium, σ^b, such that each agent chooses a_k^1 and always announces R without monitoring. Equilibrium σ^b may be plausible since σ^b Pareto-dominates $\hat{\sigma}$ from the agents' view point. However, σ_b is bad for the principal. In the following sections, we propose desirable contracts to virtually implement the first-best action pair as a plausible equilibrium with approximate first-best outcome.

4. Collusion-Proof Equilibirum

In this section, we adopt *coalition-proof Nash equilibrium* defined by Bernheim, Peleg, and Whinston (1987) as the equilibrium concept. In the two-agent case, coalition-proof Nash equilibria are the outcomes that is not Pareto-dominated by any other Nash equilibrium. Hence, we suppose that the agents can collusively choose preferable one of equilibria which is induced by the given contract. We say that an action pair is virtually implements in coalition-proof Nash equilibrium if there exists a contract virtually implements an action pair and its equilibrium is coalition-proof Nash equilibrium.

The wages are contingent not only on the messages but also on the outputs. The following condition 1 is assumed. Its role will be clear below.

Condition 1**:**

$$P(\tau) \neq P(a_1^e, a_2^e), \quad \forall \tau \in \Delta(A \backslash (a_1^e, a_2^e)),$$

where $P(a_1, a_2) = (p(x_1|a_1, a_2), \cdots, p(x_L|a_1, a_2))$ and $P(\tau) = \sum_{i,j} P(a_1^i, a_2^j) \cdot \tau(a_1^i, a_2^j)$.

Condition 1 implies that the probability distribution $P(a_1^e, a_2^e)$ can not be induced when any agent deviates the first-best action. That is, the following system has a unique solution in τ.

$$\sum_i \sum_j \tau(a_1^i, a_2^j) \cdot p(x^l | a_1^i, a_2^j) = p(x^l | a_1^e, a_2^e), \quad \forall x^l \in X,$$
$$\tau(a_1^i, a_2^j) \geq 0, \quad \forall (a_1^i, a_2^j) \in A_1 \times A_2.$$

The system has L equations and $I \times J$ inequalities. If $L \geq I \times J$, condition 1 is generically satisfied. Condition 1 is equivalent to the following[5]:

Condition $1'$ **:** There exists a vector $\hat{u} \equiv (\hat{u}(x_1), \cdots, \hat{u}(x_L))$ such that

$$P(a_1^i, a_2^j) \cdot \hat{u} > 0, \quad \forall (i,j) \neq (e,e) \quad \text{and} \quad P(a_1^e, a_2^e) \cdot \hat{u}_1 < 0.$$

When there exists a vector $\hat{u}$ satisfied with condition $1'$, for any scholar $\nu > 0$, vector $\hat{u}' = \nu \cdot \hat{u}$ also satisfies condition $1'$. Therefore, $|P(a_1^i, a_2^j) \cdot \hat{u}|$ can be made to be arbitrarilly small or large.

Consider the following contract.

	R	P
R	$C_1^e + \alpha_1$, $C_2^e + \alpha_2$	$\underline{C}_1 - \varepsilon_1(i,j)$, $C_2^e + \alpha_2 + \varepsilon_2(j,i)$
P	$C_1^e + \alpha_1 + \varepsilon_1(i,j)$, $\underline{C}_2 - \varepsilon_2(j,i)$	$\underline{C}_1$, $\underline{C}_2$

We define $\varepsilon_k(i,j) = P(a_k^i, a_{-k}^j) \cdot \hat{u}$. In this contract, for example, when (P,R) is announced and x is realized, the utility-payment for agent 1 is $v_1((P,R),x) = C_1^e + \alpha_1 + \hat{u}(x)$. The expected utility-payments are written in the above matrix given action pair (a_1^i, a_2^j). The interesting aspect of this contract is as follows: When (a_1^e, a_2^e) is chosen, announcing R is the dominant strategy for each agent in the communication stage. And if agent k chooses an action other than a_k^e, P is dominant.

We describe all the equilibrium. The iterative elimination of strictly dominated strategies reduces the normal-form representation as follows.

[TABLE 2 HERE]

[5]See Fan (1956).

(a_k^e, R) is the strategy that agent k chooses a_k^e and announces R without monitoring. Similarly, (a_k^1, P) is the strategy that he chooses a_k^1 and announces P without monitoring. (a_k^e, γ) is the strategy that he chooses a_k^e and announces R if he observe a_{-k}^e and P otherwise. Each strategy does not specify moves at the information set which can not be reached since the unspecified moves do not affect Nash equilibrium.

The process of the elimination of strictly dominated strategies is as follows. Consider agent 1. (a_1^e, P) and (a_1^1, R) are strictly dominated by (a_1^1, P). And, $(a_1^i, \cdot)$ such that $i \neq e$ is strictly dominated by (a_1^1, P) if γ is sufficiently small and $|\varepsilon(i,j)|$ is appropriately small. Finally, (a_1^e, γ) dominates $(a_k^e, \cdot)$ other than (a_k^e, R). Similarly, for agent 2, the elimination process is same. Consequently, the above matrix is induced.

In this reduced normal form game, there are only three equilibrium outcomes.

(1) $\underline{\sigma}$: Take (a_k^1, P) with probability one.

(2) $\bar{\sigma}$: Mix (a_k^1, P) and (a_k^e, γ).

(3) σ^*: Mix (a_k^1, P), (a_k^e, R), and (a_k^e, γ).

Apparently, $\underline{\sigma}$ is a Nash equilibrium. In this equilibrium, each agent's expected utility equals to zero. Let $\underline{\Sigma}$ be the set of strateies that is payoff equivalent to $\underline{\sigma}$. Then, each strategy in $\underline{\Sigma}$ is also Nash equilibrium. In set $\underline{\Sigma}$, there is unique sequential equilibrium such that agent k chooses a_k^1 and always announces P without monitoring.

In case (2), Nash equilibrium strategy is $\bar{\sigma}_k = (1 - \delta_k(\gamma))[(a_k^e, \gamma)] + \delta_k(\gamma)[(a_k^1, P)]$, for each $k = 1, 2$, where $\delta_k(\gamma)$ is the same as defined in section 3. In this equilibrium, each agent's expected utility equals to zero and the first-best action pari vurtually implementable at almost the same cost as the first-best. Let $\bar{\Sigma}$ be the set of strateies that is payoff equivalent to $\bar{\sigma}$. Then, each strategy in $\bar{\Sigma}$ is also Nash equilibrium. In set $\bar{\Sigma}$, there is unique sequential equilibrium. Agent k chooses a_k^e with probability $1 - \delta_k(\gamma)$, and a_k^1 with $\delta_k(\gamma)$. In the monitoring stage, when he chooses a_k^e, he monitors the opponent.

When he chooses a_k^i such that $i \neq e$, he does not monitor the opponents. In the communication stage, he announces R at the states $(a_k^e; a_{-k}^e)$, and P otherwise. The proof is almost the same as in section 3 and omitted.

In case (3), Nash equilibrium strategy is given as

$$\sigma_k^* = (1 - x_k(\gamma) - y_k(\gamma)) \cdot [(a_k^e, \gamma)] + x_k(\gamma) \cdot [(a_k^e, R)] + y_k(\gamma) \cdot [(a_k^1, P)],$$

where

$$x_k(\gamma) = \frac{\alpha_k \left(1 - \frac{\gamma}{\varepsilon_{-k}(e,1)}\right) - \gamma \left(1 + \frac{\Delta_k^e}{\varepsilon_{-k}(e,1)}\right)}{\Delta_k^e + \varepsilon_{-k}(e,1) + \alpha_k}, \quad y_k(\gamma) = \frac{\gamma}{\varepsilon_{-k}(e,1)}.$$

Let Σ^* be the set of strateies that is payoff equivalent to σ^*. Then, each strategy in Σ^* is also Nash equilibrium. In set Σ^*, there is unique sequential equilibrium. Agent k chooses a_k^e with probability $1 - y_k(\gamma)$, and a_k^1 with $y_k(\gamma)$. In the monitoring stage, when he chooses a_k^e, he monitors with probability $\frac{1-x_k(\gamma)-y_k(\gamma)}{1-y_k(\gamma)}$, and does not with $\frac{x_k(\gamma)}{1-y_k(\gamma)}$. When he chooses a_k^i such that $i \neq e$, he does not monitor the opponents. In the communication stage, he announces R at the states $(a_k^e; a_{-k}^e)$ and $(a_k^e; \phi)$, and P otherwise.

If we put $\alpha_k = \gamma^\kappa$, where $0 < \kappa < 1$, then $x_k(\gamma) > 0$ and $y_k(\gamma) > 0$ hold. And it is held that $\lim_{\gamma \to 0} x_k(\gamma) = 0$ and $\lim_{\gamma \to 0} y_k(\gamma) = 0$. That is, (a_1^e, a_2^e) is virtually implementable with almost the same cost as the first-best. In the equilibrium, each agent obatains the expected utility of $R_k(\gamma) = y_k(\gamma) \cdot (\Delta_{-k}^e + \alpha_k + \varepsilon(1,e)) > 0$. And, $\lim_{\gamma \to 0} R_k(\gamma) = 0$. That is, σ^* Pareto-dominates $\underline{\sigma}$ and $\bar{\sigma}$.[6]

Cnsequently, we obtains the following proposition 3.

Proposition 3: Suppose that Condition 1 holds. There exists a contract under which (a_1^e, a_2^e) is virtually implementable in coalition-proof Nash equilibrium with almost the same cost as the first-best.

[6] In the equilibrium under σ^*, agents obtain strictly positive expected utility. If each utility-payment is reduced by $R_k(\gamma)$ for each m and x, agents' expected utility can be equivalent to the reservation utilities without disturbing equilibrium. Then, under $\underline{\sigma}$ and $\bar{\sigma}$, each agent obtains negative expected utility.

5. Unique Implementation

In this section, we construct a contract that implements the first-best actions virtually and uniquely in sequential equilibrium.

Condition 2: $\qquad P(a_1^1, \tau_2) \neq P(a_1^1, a_2^e), \quad \forall \tau_2 \in \Delta_2^e \backslash \tau_2^e,$

where τ_2^e is the mixed action such that $\tau_2^e(a_2^e) = 1$ and $\tau_2^e(a_2) =$ for each $a_2 \neq a_2^e$.

This condition implies that, if agent 1 commits a_1^1, agent 2 can not induce the same probability distribution by deviating from a_2^e as $P(a_1^1, a_2^e)$. This condition is generically satisfied if $L \geq J$. Therefore, both conditions 1 and 2 are generically satisfied if $L \geq I \times J$.

Condition 2 is equivalent to the following:

Condition $2'$**:** There exists a vector $\tilde{u}_2 \equiv (\tilde{u}_2(x_1), \cdots, \tilde{u}_2(x_L))$ such that

$$P(a_1^1, a_2^e) \cdot \tilde{u}_2 - C_2^e > P(a_1^1, a_2^j) \cdot \tilde{u}_2 - C_2(a_2^j), \quad \forall j \neq e.$$

That is, when agent 1 commits the least cost action a_1^1, there exists a vector $\tilde{u}_2$ that makes agent 2 strictly prefer to taking a_2^e. If there exists such a vector $\tilde{u}_2$, then, for any schalar $\eta \in \mathscr{R}$, $\hat{u}_2 = (\tilde{u}_2(x_1) + \eta, \cdots, \tilde{u}_2(x_L) + \eta)$ satisfies condition $2'$.

Let $\tilde{U}_2$ be the set of $\tilde{u}_2$ that satisfies condition $2'$. We denote $\tilde{u}_2(i,j) = P(a_1^i, a_2^j) \cdot \tilde{u}_2$. Then, there exists a $\tilde{u}_2 \in \tilde{U}_2$ such that the following maximization problem has a unique solution $\hat{j}$.

$$\max_{j \neq e} \tilde{u}_2(e,j) - C_2(a_2^j).$$

Suppose that the maximization problem has multiple solutions. Say, $\hat{j}$ and ξ are the solutions. Then, if $C_2(a_2^{\hat{j}}) > C_2(a_2^{\xi})$ without loss of generality, $P(a_1^e, a_2^{\hat{j}}) \neq P(a_1^e, a_2^{\xi})$ must be held.[7] Hence, there exists a x_l such that $p(x_l|a_1^e, a_2^{\hat{j}}) > p(x_l|a_1^e, a_2^{\xi})$. If we consider a vector $\hat{u}_2$ such that

$$\hat{u}_2 = (\tilde{u}_2(x_1), \cdots, \tilde{u}_2(x_{l-1}), \tilde{u}_2(x_l) - \delta, \tilde{u}_2(x_{l+1}), \cdots, \tilde{u}_2(x_L)),$$

[7] If $P(a_1^e, a_2^{\hat{j}}) = P(a_1^e, a_2^{\xi})$, $\hat{j}$ can not be the solution since $P(a_1^e, a_2^{\hat{j}}) \cdot \tilde{u}_2 = P(a_1^e, a_2^{\xi}) \cdot \tilde{u}_2$. This contradicts the assumption that $\hat{j}$ is a solution of the maximization problem.

then it is possible to make $\hat{j}$ only the solution. In fact, there exists a $\bar{\delta}$ such that, for any $\delta \in (0, \bar{\delta})$, $\hat{j}$ is unique solution ot the maximization problem given $\hat{u}_2$. Condition $2'$ implies that $\tilde{U}_2$ is a set to be L-dimensional, open, and non empty. If $\tilde{u}_2 \in \tilde{U}_2$, then, for some $\delta > 0$, $\hat{u}_2 \in \tilde{U}_2$. The discussions below are assumed to be $\hat{j} = 1$ without loss of generality.

Consider the following contract.[8]

	R	P
R	$C_1^e + \alpha_1$, $C_2^e + \gamma$	$\underline{C}_1 - K\varepsilon_1(i,j)$, $C_2^e + \varepsilon_2(j,i) + \gamma$
P	$C_1^e + \alpha_1 + \varepsilon_1(i,j)$, Z	$\underline{C}_1$, $\tilde{u}_2(i,j)$

Assume that $\tilde{u}_2(i,j) > Z$ holds for any i, j, and $\tilde{u}_2(e,1) - \underline{C}_2 = 0$. And take $K(> 0)$ so that $-\Delta_1^e - K\varepsilon_1(e,e) > \alpha_1 > 0$. In fact, those are possible under condition 1 and 2.

For agent 1, the best respose property in the communication stage is the same as the contract in the previous section. On the other hand, for agent 2, when (a_1^e, a_2^e) is chosen, announcing R is the best response in the comminication stage if agent 1 announces R, and P is the best response if agent 1 announces P. When agent 2 chooses an action other than a_2^e, P is dominant strategy.

Table 3 below is the reduced normal form game induced by eliminating all strictly dominated strategies. For agent 1, only three strategies survive after the elimination. However, for agent 2, there are many strategies. Each strategy is defined as in the previous section.

[Table 3 Here]

The process of elimination of strictly dominated strategies for agent 1 is as same as in the previous section. Hence, (a_1^e, R), (a_1^e, γ), and (a_1^1, P) survive. Examine strictly dominated strategies for agent 2 after eliminating all strictly dominated strategies for agent 1. Strategies $(a_2^j, \cdot)$ such that $j > e$ are strictly dominated by (a_2^e, γ) if γ is sufficiently

[8]As in the previous section, expected utility-payments given (a_1^i, a_2^j) are written in each cell.

small. And (a_2^e, R) is stricly dominated by (a_2^1, P). Because, when agent 2 takes (a_2^e, R), he obtains the expected utility γ if agent 1 takes (a_1^e, R) or (a_1^e, γ), and $Z - C_2^e$ if (a_1^1, P). However, (a_2^e, P) is not strictly dominated though (a_2^e, R) is strictly dominated. And for each $1 \leq j < e$, (a_2^j, R) is strictly dominated by (a_2^j, P). Consequently, table 3 is induced.

Note that (a_1^1, P) is chosen with positive probability in any equilibrium. Suppose that (a_1^1, P) is not chosen in an equilibrium. Then, (a_1^2, P) is unique best response for agent 2 since agent 1 chooses (a_1^e, R) and/or (a_1^e, γ). Given agent 2's strategy (a_2^1, P), agent 1's best response is (a_1^1, P). Contradiction.

First, show that, in equilibrium, (a_1^e, R) can not be chosen with positive probability. Suppose that (a_1^e, R) is chosen with positive probability. From the above discussion, agent 1 must randomize between (a_1^e, R) and (a_1^1, P). Let $U_1(\sigma_1, \sigma_2)$ be expected utility given strategy (σ_1, σ_2). There must exist σ_2 such that $U_1((a_1^e, R), \sigma_2) = U_1((a_1^1, P), \sigma_2) = 0$ since $U_1((a_1^1, P), \sigma_2) = 0$ for any σ_2. That is,

$$\sigma(a_2^e, P)[-\Delta_1^e - K\varepsilon_1(e,e)] + \sigma(a_2^e, \gamma)\alpha_1 + \sum_{j<e} \sigma(a_2^j, P)[\underline{C}_2 - C_2(a_2^j) - K\varepsilon_1(e,j)] = 0.$$

Since $U_1((a_1^e, R), (a_2^e, P)) > 0$, $U_1((a_1^e, R), (a_2^e, \gamma)) > 0$, and $U_1((a_1^e, R), (a_2^j, P)) < 0$ for all $j < e$, it is satisfied that $\sum_{j<e} \sigma(a_2^j, P) > 0$. And, when α_1 is sufficiently small, there exists $j(< e)$ such that $\sigma_2(a_2^j, P) > T \cdot \alpha_1$, where $T > 0$, for any σ_2 that satisfies the above equation. Then,

$$U_1((a_1^e, \gamma), \sigma_2) - U_1((a_1^e, R), \sigma_2) = \sum_{j<e} \sigma(a_2^j, P) K\varepsilon_1(e,j) - \gamma.$$

When $\alpha_1 = \gamma^\kappa$, where $0 < \kappa < 1$, the right hand side of the equation is negative for sufficiently small γ. That is, $U_1((a_1^e, \gamma), \sigma_2) > U_1((a_1^e, R), \sigma_2)$. Hence, there does not exist equilibria such that both (a_1^e, R) and (a_1^1, P) are chosen with positive probablity.

Next, suppose that we eliminated (a_1^e, R) from table 3. Then, if agent 2 think that agent 1 would choose (a_1^e, γ) or (a_1^1, P), each (a_2^j, P) such that $1 < j < e$ is never chosen if γ is sufficiently small, since it is strictly dominated by (a_2^e, γ).

[Table 4 Here]

Hence, if, in the reduced normal form game of table 4, there exists unique equilibrium, then that implies that the game induced by the contract has unique equilibrium. Consequently, we obtains the following proposition.

Proposition 4: Suppose that condition 1 and 2 hold. Then, (a_1^e, a_2^e) is virtually and uniquely implementable in sequential equilibrium with almost the same cost as the first-best.

Proof: In table 4, pure strategy equilibrium does not exist. Mixed strategies are candidates for the equilbrium. Examine whether (a_2^e, P) would be chosen with positive probability in equilibirum. To choose (a_2^e, P) with positive probability, it is necessary to be indifferent between (a_2^e, P) and (a_2^1, P). However, $U_2(\sigma_1, (a_2^e, \gamma)) > U_2(\sigma_1, (a_2^e, P))$ holds for σ_1 such that $U_2(\sigma_1, (a_2^e, P)) = U_2(\sigma_1, (a_2^e, P))$. Therefore, mixing (a_2^e, P) and (a_2^1, P) can not be equilibrium strategy.

Consequently, there is unique Nash equilibrium outcome. Equilibrium strategy $\tilde{\sigma} = (\tilde{\sigma}_1, \tilde{\sigma}_2)$ is given by

$$\tilde{\sigma}_1 = (1 - \tilde{\delta}_1(\gamma))[(a_1^e, \gamma)] + \tilde{\delta}_1(\gamma)[(a_1^1, P)],$$

where

$$\tilde{\delta}_1(\gamma) = \frac{\gamma}{\tilde{u}_2(1, e) - \tilde{u}_2(1, 1) - \Delta_2^e} > 0,$$

and

$$\tilde{\sigma}_2 = \bar{\sigma}_2.$$

Let $\tilde{\Sigma}$ be the set of strateies which is payoff equivalent to $\tilde{\sigma}$. Then, each strategy in $\tilde{\Sigma}$ is also Nash equilibrium. In set $\tilde{\Sigma}$, there is unique sequential equilibrium: Agent k chooses a_k^e with probability $1 - \tilde{\delta}_k(\gamma)$, and a_k^1 with $\tilde{\delta}_k(\gamma)$, where $\tilde{\delta}_k(\gamma)$. In the monitoring stage, when he chooses a_k^e, he monitors the opponent. When he chooses a_k^i such that

$i \neq e$, he does not monitor the opponents. In the communication stage, he announces R at the states $(a^e_k; a^e_{-k})$, and P otherwise.

In equilibrium $\tilde{\sigma}$, the first-best action pair is chosen with almost probability one when γ is sufficiently small. And each agent obtains utility-payment C^e_k with almost probability one. That is, the first-best outcome is approximately attainable. **Q.E.D.**

Let $\tilde{R}_2(\gamma)$ be expected utility agent 2 obtains in equilibrium $\tilde{\sigma}$. It is possible that $\tilde{R}_2(\gamma) \neq 0$, that is, individual rationality condition is not bind or not satisfied. If each utility-payment is reduced by $\tilde{R}_2(\gamma)$ for each m and x, agent 2's expected utility can be equal to the reservation utility without disturbing equilibrium.

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