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TOWARD A THEORY OF HIERARCHICAL DECENTRALIZATION*

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I. Introduction

Hierarchy is one of the most commonly observed organizational forms in many of today's organizations. An organizational design problem in a hierarchy is the problem of allocating various decision authorities to the members in various positions of the hierarchy; the problem of hierarchical decentralization. We do observe nontrivial hierarchical decentralization in reality. Nontrivial hierarchical decentralization means that different members are in charge of performing different decision making tasks. We believe that nontrivial hierarchical decentralization prevails because an organization achieves better overall decision making performance than it would without nontrivial hierarchical decentralization. One naturally hopes for a theory which characterizes optimal hierarchical decentralization and relates it to what we observe in reality.

Unfortunately we are currently far from having a satisfactory theory of hierarchical decentralization. Only a few seminal works have been attempted; Barron and Besanko (1992), McAfee and McMillan (1992), Melumad, Mookherjee and Reichelstein (1991) (1992). The situation is in striking contrast to the vast literature of mechanism design which has developed in the 1980s and contributed to the great progress in the theory of organizational design.

The purpose of this paper is to set a direction of research toward a theory of hierarchical decentralization. Namely, we reconsider the reason why the theory of hierarchical decentralization has been left undeveloped in the remarkably successful literature of mechanism design. Then we clarify the basic nature of the obstacle that we must overcome in moving forward beyond the mechanism design literature so

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as to build a satisfactory theory of hierarchical decentralization. Finally, we list several theoretical issues that must be solved in order to overcome the obstacle.

II. A Formal Definition of Hierarchy

We begin by formalizing our objects of analysis: organization, hierarchy, and hierarchical decentralization.

Following a standard treatment in the mechanism design literature, we model an organization as follows. An organization is set $I = \{0, 1, \dots, n\}$ of $n + 1$ members. The member $i = 0$ represents the organization and is called the Principal. Any other member $i \in I \setminus 0$ is called an Agent. Each member $i \in I$ takes an action a_i from some set A_i of feasible actions and receives money transfer $x_i \in \mathbb{R}$. A pair $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ of an action profile and a money transfer profile constitutes a decision of the organization. The Principal's utility from a decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ is represented as $B((a_i)_{i \in I}) + x_0$ by some function $B : \prod_{i \in I} A_i \rightarrow \mathbb{R}$ which evaluates an action profile chosen. Agent i 's utility is $x_i - C_i(a_i, \theta_i)$. Here the function $C_i : A_i \times \Theta_i \rightarrow \mathbb{R}$ evaluates the Agent i 's cost of taking action a_i where the parameter θ_i is a realization of random variable $\tilde{\theta}_i$ in a support Θ_i . A realization θ_i is a private information of Agent i . Decision making in the organization is to choose a decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ by processing an information profile $(\theta_i)_{i \in I \setminus 0}$. As a representative of the organization, the Principal wants to maximize his utility by guiding decision making properly.

Hierarchy is a structure of an organization and is used to give order to a process of decision making. A hierarchy in this sense is defined as a pair $\langle \succ, \rightarrow \rangle$ of two binary relations over set I . A binary relation $\succ$ is called ranking. For members $i, j \in I$, $i \succ j$ reads as saying that member i is superior to member j in the ranking $\succ$. A ranking defines an authority relationship in an organization. Namely, member $i \in I$ is assigned a decision authority to choose an action a_j or a money transfer x_j relevant to member j only if it is either that i and j are the same individual or that i is superior to j . For precisely defining an authority relationship, we assume that a ranking $\succ$ is an arborescence with a single root of Principal. By assumption, any member $i \in I$ is uniquely associated with a subgroup $I(i) = \{i\} \cup \{j \in I \mid i \succ j\}$ over which i can have decision authority. Also Agent $i \in I \setminus 0$ is uniquely associated

with his immediate superior $b(i) \in I$ such that $b(i) \succ i$ and that $j \succ b(i)$ for any other superior $j \succ i$. The uniqueness of an immediate superior means the uniqueness of the authority line.

A binary relation $\rightarrow$ is called communication channel. For members $i, j \in I$, $i \rightarrow j$ reads as saying that member i has a communication channel to member j . A communication channel defines the possibility to transmit information from one member to another in the organization. Namely, member i can send a message to member j only if i has a communication channel to j .

A pair $\langle \succ, \rightarrow \rangle$ of a ranking and a communication channel is called a hierarchy if and only if

$$\forall i \neq j \in I; i \rightarrow j \text{ iff } i = b(j) \text{ or } j = b(i).$$

Using words, a hierarchy is such a pair of authority relationship and communication possibility that two members can exchange information if and only if they are connected directly in a vertical authoritative relationship. A hierarchy can be used to guide decision making in an organization because decision and information are ordered in a single direction so that a decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ is reached in a consistent manner. By consistency, we mean two things. First, the decision of one variable is consistent with the decision of another variable because a decision relevant to member i is made by himself or by his superior j and the superior j 's decision is affected possibly by a superior k of the superior j via k 's decision relevant to j and so on, so that the governance of decision making is ordered in a single line of authority ending with the Principal and is never messed up in a cycle. Second, the decision of one variable is consistent with information necessary for the decision because, when member j makes a decision relevant to his subordinate i , it is guaranteed that j has access to information about θ , via a chain of communication channels connecting j and i .

The problem of hierarchical decentralization is a problem of allocating decision authorities in a given hierarchy $\langle \succ, \rightarrow \rangle$. The notion of "decentralization" is specifically adequate as an expression to signify an allocation of decision authorities in a hierarchy. Consider any member $i \in I$ and a decision, say a_i , relevant to him. The ranking $\succ$ defines a unique chain $j_{l(i)} \succ j_{l(i)-1} \succ \dots \succ j_2 \succ j_1$ of members such that $j_{l(i)}$ is the Principal, j_1 is member i , and $j_{l+1} = b(j_l)$ for any $l \in \{1, 2, \dots, l(i)-1\}$. The definition of hierarchy requires that an authority

to choose a_i must go to one of $j_{l(i)}, j_{l(i)-1}, \dots, j_2, j_1$. If it goes to $j_{l(i)}$, it means that the decision of a_i is centralized to the Principal. If it goes to j_1 , it means that the decision of a_i is decentralized to Agent i himself. If it goes to j_l in general, the integer l relative to $l(i)$ measures the degree of centralization. Thus, in a hierarchy, an allocation of a decision authority is to determine a degree of decentralization.

III. The Problem of Mechanism Design

Why has the theory of hierarchical decentralization been left undeveloped? The reason lies in the assumptions under which the mechanism design literature analyzes the issue of organizational design.

The issue of organizational design is a problem of finding an optimal procedure of decision making. The Principal designs a procedure and proposes it to Agents. Knowing his private information and expecting what will happen if the procedure is implemented, each Agent decides whether to accept or reject the proposal. If at least one Agent rejects it, all the members get their reservation utilities. An Agent will effectively reject it if there is a chance that he comes to his move knowing that the implementation of the procedure will give him an expected utility strictly less than the reservation utility, and therefore, he should not continue to make a move in the procedure.¹ On the other hand, if all the Agents accept it, the procedure is committed and implemented. The Principal designs a procedure so as to maximize his expected utility from a decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ arrived by its implementation.

The object of design includes all the aspects of procedure. Especially, it includes design of authority relationship and communication channel. The driving force for optimality is a trade off between a benefit from a better decision based on more information about a parameter realization profile $(\theta_i)_{i \in I \setminus 0}$ and a cost of getting more information necessary for a better decision.

There are two fundamental cost factors in making a better decision by using more information. One factor is communication cost.

1. An alternative criterion for rejection is that the ex ante expected utility from the procedure before implementation is strictly less than the reservation utility.

As long as the Principal wants decision making to reflect the informations θ_i ($i \in I \setminus 0$) in a nontrivial way, some communication between members is unavoidable since the informations are owned by Agents in a decentralized way so that any single member as a decision maker can not make a consistent decision without communication. If it takes some cost for Agent i to send any message about θ_i , directly or indirectly, to a decision maker of a relevant variable, say a_i , then the cost must come into the Principal's cost calculation of any decision making procedure under which the decision maker decides the variable relying on a message from Agent i . Hence an optimal procedure must reflect the relative costs of communications between members.

The other factor is incentive cost. Suppose in a procedure that member j is in charge of deciding a variable, say a_i , relevant to another Agent i . Suppose also that the procedure asks Agent i to hand some information about a realization θ_i , directly or indirectly, to member j so that member j can base his decision of a_i on the information. Then Agent i should be careful enough in preventing member j from using the released information for member j 's own interest. If member j 's interest is in conflict with member i 's interest, member i might hesitate to release the information. The Principal must count the cost if he wants member j 's decision to be based on the information and he needs to overcome Agent i 's hesitation in releasing the information.

The mechanism design literature developed so far focuses on the latter cost and assumes that any communication in organization is costless. This assumption implies two things. The first implication is that any procedure for decision making is a communication game in extensive form. In a communication game, a move by a member is either to send a costless message to another member or to make a decision which he is in charge of. At each terminal node, a decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ must be arrived at as a combination of decisions made along the path to the terminal node. Communication is costless in the communication game since members' utilities at a terminal node is based solely on the decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ arrived there and independent of a history of messages sent along the path to the terminal node. Such a communication game is represented in normal form by a profile $(S_i)_{i \in I}$ of each member i 's communication-decision strategy space and by a pair of outcome functions $\alpha = (\alpha_i)_{i \in I}, \xi = (\xi_i)_{i \in I}$. For each strategy profile $(s_i)_{i \in I} \in \prod_{i \in I} S_i$, the outcome function $\alpha_i : \prod_{i \in I} S_i$

$\rightarrow A_i$ defines the member i 's action $\alpha_i((s_i)_{i \in I})$ taken at the terminal node reached by a play according to the strategy profile $(s_i)_{i \in I}$ in the communication game while the outcome function $\xi_i: \prod_{i \in I} S_i \rightarrow \mathbb{R}$ defines the money transfer $\xi_i((s_i)_{i \in I})$ to member i there. Given that a realization θ_i is an Agent i 's private information, a communication game $\langle (S_i)_{i \in I}, (\alpha_i)_{i \in I}, (\xi_i)_{i \in I} \rangle$ constitutes a Bayesian game with strategy spaces $\Sigma_0 = S_0$ and $\Sigma_i = S_i^{\theta_i}$ for each $i \in I \setminus 0$. Decision making by a procedure $\langle (S_i)_{i \in I}, (\alpha_i)_{i \in I}, (\xi_i)_{i \in I} \rangle$ is an implementation of some Bayesian equilibrium $\sigma^* = (\sigma_i^*)_{i \in I} \in \prod_{i \in I} \Sigma_i$ in the corresponding Bayesian game. The implementation induces an allocation rule, a pair of functions $a = (a_i)_{i \in I} : \prod_{i \in I \setminus 0} \Theta_i \rightarrow \prod_{i \in I} A_i$ and $x = (x_i)_{i \in I} : \prod_{i \in I \setminus 0} \Theta_i \rightarrow \mathbb{R}^I$ which assigns to each parameter realizations $(\theta_i)_{i \in I \setminus 0}$ a decision $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ actually made, by

$$\forall (\theta_i)_{i \in I \setminus 0} \in \prod_{i \in I \setminus 0} \Theta_i ; \quad \begin{aligned} a_i((\theta_i)_{i \in I \setminus 0}) &= \alpha_i((\sigma_i^*(\theta_i))_{i \in I}) \\ x_i((\theta_i)_{i \in I \setminus 0}) &= \xi_i((\sigma_i^*(\theta_i))_{i \in I}). \end{aligned}$$

The important fact is that such an allocation rule necessarily satisfies individual incentive compatibility conditions

$$\begin{aligned} \forall \theta_i, \theta'_i \in \Theta_i ; \quad & E_{\theta_{-i}}[x_i(\theta_i, \theta_{-i}) - C_i(a_i(\theta_i, \theta_{-i}), \theta_i)] \\ & \geq E_{\theta_{-i}}[x_i(\theta'_i, \theta_{-i}) - C_i(a_i(\theta'_i, \theta_{-i}), \theta_i)] \quad (1) \end{aligned}$$

where we denote $\theta_{-i} \equiv (\theta_j)_{j \in I \setminus 0, j \neq i}$. The fact is a main part of what is called the revelation principle.

The second implication of the costless communication assumption is that a special decision making procedure is feasible; a direct revelation mechanism. The mechanism is a communication game in which all the Agents announce their private informations to the Principal independently and simultaneously, and a decision is prespecified depending solely on the announcements. The game is such that $S_0 = \emptyset$ and $S_i = \Theta_i$ for each $i \in I \setminus 0$. A direct revelation mechanism is one of the feasible decision making procedures since any message can be sent costlessly to the Principal directly from any Agent.

The two implications combined together lead to what is called the revelation principle. Namely, it is enough and possible for the Principal to choose a best direct revelation mechanism according to his own interest. This is true because, for any communication game $\langle (S_i)_{i \in I},$

$(\alpha_i)_{i \in I}, (\xi_i)_{i \in I}$ and any Bayesian equilibrium σ^* of the game, the induced allocation rule $(a_i)_{i \in I}, (x_i)_{i \in I}$ defines a special direct revelation mechanism $\langle (\Theta_i)_{i \in I \setminus 0}, (\hat{a}_i)_{i \in I}, (\hat{\xi}_i)_{i \in I} \rangle$ by $\hat{a}_i = a_i$ and $\hat{\xi}_i = x_i$ for each $i \in I$. By the individual incentive compatibility conditions (1), truth telling constitutes a Bayesian equilibrium of the direct revelation mechanism. The direct revelation mechanism is feasible and supports the same allocation rule by its construction. Hence the Principal can find an optimal procedure within the class of direct revelation mechanisms.

The revelation principle in the above form undermines a motivation to study the problem of optimal hierarchical decentralization. As long as a direct revelation mechanism is available with zero communication cost, the problem of organizational design is solved by an optimal direct revelation mechanism. Also a technique to compute an optimal direct revelation mechanism has been well developed. Hence it is unnecessary to examine whether other organizational decision making procedures can also achieve the best performance without relying on a direct revelation mechanism. Until recently an analysis has not been attempted around an issue of how close a hierarchy can perform relative to an optimal direct revelation mechanism.

However, in the problem of hierarchical decentralization, design of authority relationship and communication channel is not control variables for the Principal but exogenously given to the organization. A direct revelation mechanism is not feasible anymore.

IV. Nature of Difficulties in the Theory of Hierarchical Decentralization

What is the nature of difficulties when we attempt to evaluate an optimal hierarchical decentralization? The costless communication assumption in the mechanism design literature must be abandoned since a direct revelation mechanism is not available anymore. However not all the implications of the assumption become useless.

In the theory of hierarchy, the costless communication assumption can be replaced by an assumption of costless communication via communication channel. Namely, in a hierarchy $\langle \succ, \rightarrow \rangle$, we assume that a message can be sent from member i to member j costlessly if and

only if $i \rightarrow j$ and that a message can be sent from member i to member j with an infinite cost if and only if $i \not\rightarrow j$. Then any meaningful procedure for decision making in a hierarchy is a communication game $\langle (S_i)_{i \in I}, (\alpha_i)_{i \in I}, (\xi_i)_{i \in I} \rangle$ such that a strategy space S_i is confined to one where any move of member i in the extensive form does not allow a possibility of sending a message to any member j with $i \not\rightarrow j$. Hence the effect of examining decision making procedures in a hierarchy is to abandon the second implication of the costless communication but to maintain the first implication in a modified way by restricting the strategy spaces of communication games.

The restriction of the strategy spaces does not alter the conclusion of the first implication, namely, the conclusion that any pair of allocation rules implied by a Bayesian equilibrium satisfies the individual incentive compatibility conditions (1). Hence it continues to be the case that performance of any procedure for decision making in a hierarchy is replicated by a truth telling equilibrium in a hypothetical direct revelation mechanism.

The difficulty comes after this point. In many cases, the class of hypothetical direct revelation mechanisms which replicate performances of decision making procedures in a hierarchy is strictly and crucially smaller than the class of direct revelation mechanisms which supports truth telling equilibria. For example, consider an organization of the Principal, Agent 1, and Agent 2 in which the Principal desperately wants to procure one unit of an indivisible product from one of the Agents at the lowest possible price. For $i=1,2$, let $a_i = 1$ denote Agent i 's action of producing the product and $a_i = 0$ denote his action of not producing it. Suppose that θ_i is Agent i 's cost of producing the product and follows the uniform distribution on $[0,1]$ independently. Then it is well known that a truth telling equilibrium is supported in a direct revelation mechanism $\langle (\Theta_i)_{i \in I \setminus 0}, (\hat{\alpha}_i)_{i \in I}, (\hat{\xi}_i)_{i \in I} \rangle$ shown in Table 1.

Table 1

	$\theta_1 \leq \theta_2$	$\theta_1 > \theta_2$
$\hat{\alpha}_1(\theta_1, \theta_2)$	1	0
$\hat{\alpha}_2(\theta_1, \theta_2)$	0	1
$\hat{\xi}_0(\theta_1, \theta_2)$	$-\frac{\theta_1 + 1}{2}$	$-\frac{\theta_2 + 1}{2}$
$\hat{\xi}_1(\theta_1, \theta_2)$	$\frac{\theta_1 + 1}{2}$	0
$\hat{\xi}_2(\theta_1, \theta_2)$	0	$\frac{\theta_2 + 1}{2}$

It is also well known that the mechanism of Table 1 is optimal. However, the outcome of Table 1 is never supported by any decision making procedure in a hierarchy $\langle \succ, \rightarrow \rangle$ such that Principal $\succ$ Agent 1 $\succ$ Agent 2. Suppose, to the contrary, that it is so. The definition of hierarchy implies that the authority to choose a_1, x_1 must go to either the Principal or Agent 1. Imagine a case where a decision making procedure in which the Principal chooses both a_1 and x_1 supports an allocation rule $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ by a Bayesian equilibrium and the allocation rule is identical to the outcome of Table 1. In the communication game in extensive form representing the procedure, the Principal's final decision of a_1, x_1 must depend solely on a history of messages sent from Agent 1 to the Principal. Among those histories, there must exist one to which the Principal chooses $a_1=1, x_1=1$. Otherwise the identities $a_1(\theta_1, \theta_2) = \hat{a}_1(\theta_1, \theta_2), x_1(\theta_1, \theta_2) = \hat{x}_1(\theta_1, \theta_2)$ fail to hold for the realizations $\theta_1=1, \theta_2=1$. Then given the Principal's equilibrium strategy, whatever apair (θ_1, θ_2) of parameter realizations is, Agent 1 must be induced to behave at all his moves in such a way that a resulting history of messages sent from Agent 1 to the Principal necessarily turns out to be the one above for the decision $a_1=1, x_1=1$. Agent 1 must be induced in such a way because $a_1=1, x_1=1$ is the best possible outcome for Agent 1 among the possible outcomes in Table 1 irrespective of his parameter realization θ_1 . Hence $a_1(\theta_1, \theta_2)=1, x_1(\theta_1, \theta_2)=1$ for any $\theta_1 \in \Theta_1, \theta_2 \in \Theta_2$. This is a contradiction to the hypothesis that $a_1(\theta_1, \theta_2) = \hat{a}_1(\theta_1, \theta_2), x_1(\theta_1, \theta_2) = \hat{x}_1(\theta_1, \theta_2)$ for any $\theta_1 \in \Theta_1, \theta_2 \in \Theta_2$. Other cases in which Agent 1 chooses either a_1, x_1 , or both also lead to contradictions.

The difficulty arises because the restriction of the strategy spaces in communication games in a hierarchy implies extra conditions to a truth telling equilibrium of a hypothetical direct revelation mechanism. Consider the above example of procurement in a hierarchy. Consider the case in which the Principal chooses a_1, x_1 . Consider any communication game in the hierarchy and any Bayesian equilibrium. Let $\langle (a_i)_{i \in I}, (x_i)_{i \in I} \rangle$ be the induced allocation rule. For each $\theta_1 \in \Theta_1$, let a correspondence $P_{\theta_1} : \Theta_2 \rightarrow 2^{\Theta_2}$ be a partition of the space Θ_2 by

$$\begin{aligned} & \forall \theta_2 \in \Theta_2 ; \theta'_2 \in P_{\theta_1}(\theta_2) \\ & \iff \\ & \forall i \in I; a_i(\theta_1, \theta_2) = a_i(\theta_1, \theta'_2), x_i(\theta_1, \theta_2) = x_i(\theta_1, \theta'_2). \end{aligned}$$

The definition of the hierarchy implies that any information about θ_2 must be transmitted as a message from Agent 2 to Agent 1 and then further transmitted as a message from Agent 1 to the Principal. The information transmission reflects itself in the extensive form of the communication game in such a way that if an Agent's information set comes before a Principal's information set along a path in the extensive form, the former information set is smaller than the latter in terms of projection to the space Θ_2 . Hence along an equilibrium path for any realizations $\theta_1 \in \Theta_1$, $\theta_2 \in \Theta_2$, Agent 1 necessarily comes to an information set which contains finer information about θ_2 than $P_{\theta_1}(\theta_2)$. Therefore, if Agent 1 wishes, he can always choose any outcome among $(a_1(\theta_1, \theta'_2), x_1(\theta_1, \theta'_2))_{\theta'_2 \in \Theta_2}$. This implies that

$$\begin{aligned} \forall \theta_1 \in \Theta_1, \forall \theta_2, \theta'_2 \in \Theta_2; x_1(\theta_1, \theta_2) - C_1(a_1(\theta_1, \theta_2), \theta_1) \\ \geq x_1(\theta_1, \theta'_2) - C_1(a_1(\theta_1, \theta'_2), \theta_1). \end{aligned} \quad (2)$$

This is the extra condition that a hypothetical direct revelation mechanism must satisfy in addition to (1) so as to replicate an outcome supported by a decision making procedure in which the Principal chooses a_1, x_1 in the hierarchy.

The obstacle for a satisfactory theory of hierarchical decentralization is a characterization of the extra conditions like (2) that in an arbitrary hierarchy a hypothetical direct revelation mechanism must satisfy in order to replicate a decision making procedure. The characterization is a hard task and no successful research has been attempted so far.

V. Issues Toward a Theory of Hierarchical Decentralization

When we go beyond the mechanism design literature toward a theory of hierarchical decentralization, the most important departure in terms of analysis is that an extensive form of communication game critically matters. The virtue of direct revelation mechanisms is that their extensive forms are degenerate so that members move only once in a play and the only information available for each member in his move is his own private information. Thanks to this virtue, the mechanism design literature need not worry about a situation in which a member strategically moves given partially revealed information about other

Agents' parameter realizations in a communication game. In a hierarchy, however, if some information needs to be transmitted vertically along some authority line, then a communication game representing such information transmission necessarily involves a nondegenerate extensive form. Namely, the moves of such information transmission must be sequential. Hence the sequential rationality matters in a communication game for a hierarchy. This is the reason why the extra condition (2) persists in the example of Section 4 even though the mechanism design literature need examine the individual incentive compatibility conditions (1) only.

One of the most important factors to sequential rationality in an extensive form game is a specification of information available at each move. In a communication game, it is a specification of timing of communications. One immediate issue is one of relative timing of communication and decision making. Consider the procurement example of Section 4 and consider the case in which the Principal decides x_1 paid by the Principal himself while Agent 1 decides a_1, a_2 , and x_2 paid by Agent 1. The issue of relative timing in this case is one of whether the Principal should decide x_1 before or after Agent 1 communicates with Agent 2 for his decisions a_1, a_2, x_2 . It is easy to see that the Principal should decide before Agent 1 talks with Agent 2. By a similar argument as in Section 4, it turns out to be the case that the money transfer x_1 must be independent of any message in any communication game. Therefore the question is whether the constant necessary payment x_1 is lower or higher when the Principal decides before Agent 1 talks with Agent 2. If the Principal decides before, the Principal can convince Agent 1 by saying that Agent 1 should expect his continuation utility in the game by taking expectation with respect to $\tilde{\theta}_2$. Agent 1 has nothing to say to the Principal against this argument. On the other hand, if Agent 1 communicates with Agent 2 before the Principal approaches Agent 1, then Agent 1 can use the information about θ_2 that he has obtained from Agent 2. Namely, Agent 1 can claim that the realization θ_2 is the worst case that Agent 1 can expect to hear from Agent 2. The claim is convincing given that the Principal knows that Agent 1 already gets some information about θ_2 from Agent 2. Therefore the Principal must pay more to compensate such a worst case possibility.

Another issue is one of relative timing of various communications.

For example, consider a hierarchy $\langle \succ, \rightarrow \rangle$ in which some member i has two distinct direct subordinates j, k with $i = b(j) = b(k)$ and the subordinate j has his own nondegenerate subgroup $I(j)$ with $|I(j)| \geq 2$. Then for any subordinate $l \in I(j)$ of the subordinate j , member j necessarily knows about θ_l better than member i . This is true in any communication game as illustrated in the example of Section 4. However timing of communications matters in the hierarchy because the informational advantage is not necessarily one way in this case. Member i necessarily knows about θ_k better than member j since any information about θ_k must be transmitted up from member k to member i and then transmitted down from member i to member j . The relative informational advantages between member i and member j depends on whether member i communicates with the subordinate k before or after member j communicates with the subordinate l .

Depending on a specification of timing of various moves as above, the extra conditions like (2) appear in a different form. Accordingly, performance of a certain way of hierarchical decentralization crucially depends on such a specification. As to the issue of timing of communication and decision, McAfee and McMillan (1992) examined the extent of loss incurred when communication takes place upwards along a single line of authority before a decision is made by the Principal at the top of the line. Barron and Besanko (1992) and Melumad, Mookherjee, and Reichelstein (1991) showed that there remains a certain loss relative to an optimal direct revelation mechanism even when a decision is made at a higher level of a hierarchy before communication takes place at a lower level of the hierarchy. The issue of timing of various communications has been untouched. Research should be conducted to explore a general relation between a specification of an extensive form of communication game and a resulting form of the extra conditions like (2).

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