Coordination, Adaptation to an Uncertain Environment and Information Processing

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One of the important aspects of organizing a firm concerns the coordination of the various tasks that must be performed by the constituent members of the organization. Thus, the firm has to decide about the optimal division of labor among its members. This requires defining the set of tasks that need to be performed by each with the aim of ensuring a nonwasteful performance of interrelated tasks that affect firm value. The firm also has to allocate decision rights across its members (i.e., decide on the set of authority relationships) and design how to gather and transmit information among them (i.e., decide on information channels); as a result of defining the set of authority relationships and designing the corresponding information channels, a hierarchy within the organization is determined. It is worth noting that coordination operates at different levels, but such levels also interact among themselves in a way that also requires coordination efforts. For example, production of a good may require coordinating the purchase of raw materials and their transportation to a factory, where workers in an assembly line may have to be coordinated to produce a final good. In turn, sales of the goods produced may require coordinating the advertising of the good and the search for customers, but such marketing activities may need to be coordinated with productive activities to avoid inefficiencies: for instance, advertising might have to be done while the product is being manufactured. Coordination therefore needs to be in the small and in the large.

1 Coordination problems and equilibrium multiplicity

In what follows, we consider an environment in which there are two individuals, called "agents," who form part of the same organization, perhaps because they have formed a partnership to conduct some economic activity. We start by analyzing the nature of coordination problems between them under the assumption that they share the same objectives, an approach known as "team theory" (Marschak and Radner, 1972), which emphasizes coordination problems and the role of information gathering and transmission in solving them. We will rely on the game-theoretic toolkit to analyze the problems faced by the team and how one can solve them.

Coordination problems between agents forming a team arise because each must take an action that affects their joint payoff, each has access to a different piece of information, and both such pieces of information are payoff-relevant. In some cases, the piece of information unavailable to the other agent could be the action itself if it cannot be observed by the other agent, perhaps because actions must be taken at the same time. This is the first scenario will analyze, but we will later extend this setting to one in which agents face environmental uncertainty, since this is an aspect that can severely exacerbate coordination problems.

To give a simple example of why the two agents may fail to coordinate on efficient behavior, consider a one-shot interaction between them and suppose that an agent's action is effort to be exerted, a binary variable. Let $\pi(e_1, e_2) = 11e_1e_2$ denote the gross payoff jointly generated by both agents when agent $i \in \{1, 2\}$ exerts effort $e_i \in \{0, 1\}$, and let $C_i(e_i) = 6e_i$ denote agent i's effort cost, $i = 1, 2$. If each agent cares about the total payoff that their collaboration generates, the (net) payoff matrix of the game they play is as follows:

	$e_2 = 0$	$e_2 = 1$
$e_1 = 0$	$0, 0$	$-6, -6$
$e_1 = 1$	$-6, -6$	$-1, -1$

Two Nash equilibria exist: one in which each agent follows the decision rule of exerting no effort and another one in which agent $i \in \{1, 2\}$ follows the decision rule of choosing $e_i = 1$. So even if there is no conflict of interest between both agents, there can be many ways in which agents' expectations can be rationally fulfilled: in particular, exerting no effort constitutes an agent's best response when she expects the other one not to exert any effort. If possible and not too costly, communication before actions are taken can clearly help agents to coordinate their effort choices and avoid a suboptimal outcome.

Another way in which the firm can attain coordination is by setting up institutional rules such as protocols put in place to confront various contingencies and make actions taken predictable. This could be achieved by having another individual to instruct agents how to behave, perhaps in face of a variety of contingencies. Such a coordinator could be a (middle) manager or headquarters.

2 Coordinated adaptation and the (de)centralization of information

The role of a coordinator is more salient when each agent can acquire some valuable payoff-relevant information that becomes private to her but may be transmitted if she is asked to do so before actions are taken.[1] Such acquisition and possible transmission of information can allow the firm to better adapt to an uncertain environment in a coordinated fashion, but it may be costly. On the one hand, the costs are clear: both the gathering of information and its transmission are costly and time-consuming activities. On the other hand, as agents acquire more information, the firm expects to adapt more easily to the various realizations of an uncertain environment: the instructions given to an agent who gathers the information but does not transmit it to the coordinator can be contingent on the gathered information. This capability

[1] There is no conflict of interests in a team-theoretic framework such as the one we are considering, so an agent has no incentive to strategically withhold or manipulate such private information to her own benefit if asked to reveal it (Talk about soft/unverifiable information (subject to unverifiable distortion) and hard/verifiable information (can only be withheld).).

to react to environmental shocks is accentuated when the coordinator is involved because the coordinator can not only give instructions contingent on the various realizations of the uncertain environment, but also prevent miscoordination. Also, as agents transmit more and more information to the coordinator, the coordinator's instructions can be based on more and more information and thus be more accurate.

The optimal organizational form adopted by the firm must optimally balance the costs and benefits of (coordinated) adaptation to an uncertain environment, where the organizational form refers in this simple setting to: (i) the pieces of information to which each agent has access, and (ii) the set of strategies for each of them. In a team-theoretic framework such as the one we consider, there is no conflict of interest and the coordinator's instructions are perfectly followed, so they can be treated as prescriptions: the coordinator effectively controls the agents' actions following communication.

To formally study the costs and benefits of adapting in a coordinated manner to an uncertain environment, let us suppose that $\pi(e_1, e_2) = 11e_1e_2$ and $C_i(e_i) = \widetilde{c}_i e_i$, where $\widetilde{c}_i$ is a binary random variable that is independently drawn and takes values 2 and 10 with equal probability. The realization of $\widetilde{c}_i$ is unknown to everybody, but agent $i \in \{1, 2\}$ has the opportunity to learn something about it before choosing effort. In particular, the agent observes an independently drawn signal that perfectly reveals the realization of $\widetilde{c}_i$ with probability $p \in [0, 1]$, but it is null (completely uninformative) with probability $1-p$.[2] So p represents how precise is the information learnt by agents from an ex-ante standpoint: precision or accuracy is maximal if $p = 1$ and minimal if $p = 0$. Assuming that the organization aims at maximizing its expected payoff, note that an agent's expected cost of exerting effort is equal to $(1/2)2 + (1/2)10 = 6$, so the only reason why it makes sense to exert effort is because at least one of the realizations of $\widetilde{c}_1$ and $\widetilde{c}_2$ is known to be equal to 2. For instance, when one of the realizations of $\widetilde{c}_1$ and $\widetilde{c}_2$ is known to be equal to 2 but the other realization is unknown, the total cost of exerting effort is expected to be equal to

[2]Because the signal of agent i is independently drawn, whether the signal is null or perfect does not depend on the realization of $\widetilde{c}_i$, so observing the signal conveys no information about such realization.

$2+(2+10)/2 = 8 < 11$; when one of the realizations of $\widetilde{c}_1$ and $\widetilde{c}_2$ is known to be equal to 10 but the other realization is unknown, the total cost of exerting effort is equal to $10+(2+10)/2 = 16 > 11$ in expectation.

Given this uncertainty about the payoff to their effort choices, the assumption that agents maximize expected net payoff yields that the payoff matrix of the game they play is as follows:[3]

	$e_2 = 0$	$e_2 = 1$
$e_1 = 0$	$0, 0$	$-6, -6$
$e_1 = 1$	$-6, -6$	$-1, -1$

Based on a coordinator's prescriptions aimed at dealing with equilibrium multiplicity, both agents should not exert any effort. However, making effort decisions based on the signals that each agent privately observes opens to door to increasing the firm's expected payoff. Henceforth, we shall say that there is centralization of information if the signals received by the agents are shared with each other or with the coordinator. In this team-theoretic setting in which there are no conflicts of interest, this is an irrelevant aspect (e.g., the coordinator could be one of the agents), so we will assume that information is centralized by the coordinator if the agents' signals are shared. When the signals are not shared, information will be said to be decentralized. Even in these cases, there is an ex-ante expected gain from conditioning effort choices on the signals that will be observed.

In what follows, we shall consider the relative (dis)advantages of centralizing and decentralizing information in various ways. We initially leave costs of information gathering and communication aside, even though they will later turn out to be critical drivers of the way in which the organization deals with information.

2.1 Centralization with full information

In this situation, the coordinator receives both signals and then provides the agents with instructions. The only scenario in which the coordinator will instruct the agents

[3] If agent $i \in \{1, 2\}$ exerts effort $e_i = 1$, total costs equal $6(1+1) = 12$ in expectation and gross payoff equals 11, so the expected net payoff they generate equals -1.

to exert effort requires that the following two events happen at the same time: (i) one of the signals must be perfect and must reveal that the effort cost is equal to 2 for the agent receiving the signal, and; (ii) the other agent must either receive a null signal or a perfect signal that reveals that her effort cost is equal to 2. In any other scenario, the coordinator will instruct the agents not to exert effort, so the firm will gain nothing.

Anticipating this optimal way of proceeding depending on the information that signals will convey, the payoff expected by the firm before agents receive the information to transmit will be equal to

$$\Pi^C = \left(\frac{p}{2}\right)^2 (11-2-2)+p(1-p)\left[11-2-\left(\frac{1}{2}2+\frac{1}{2}10\right)\right]+\left[1-\left(\frac{p}{2}\right)^2-p(1-p)\right]0.$$

To undertand this expression, note that there is probability $(p/2)^2$ that both agents observe a perfect signal that reveals an effort cost equal to 2,[4] in which case the firm's payoff is equal to $11-2-2=7$. The other case in which both agents exert effort happens when one of the agents receives a null signal and the other receives a perfect signal that reveals that her effort cost is 2, an event that has a probability equal to $(1-p)(p/2)+(1-p)(p/2)=(1-p)p$. Conditional on this event, the firm's expected profit equals $11-2-6$, since the agent with the null signal has an effort cost of 2 or 10 with equal probability, and the other agent's effort cost has been revealed to be equal to 2. Straightforward manipulations yield that

$$\Pi^C = \frac{p(12-5p)}{4} > 0.$$

[4] The probability that a particular agent observes a perfect signal is p, whereas there is one-half probability that such an agent turns out to have an effort cost equal to 2, so $p/2$ is the probability that the agent observes a perfect signal that reveals an effort cost equal to 2. As a result, $(p/2)^2$ is the probability that each of the two agents observes a perfect signal that reveals an effort cost equal to 2.

2.2 Centralization with partial information

In this case, the coordinator receives a single signal from one of the two agents, so two situations may arise when the coordinator must decide on the instructions. If the signal is perfect and reveals that the agent's effort cost is 2, an event that has a probability equal to $p/2$, then it is optimal to instruct both agents to exert effort, since the total effort cost is expected to be equal to $2 + (1/2)2 + (1/2)10 = 8$; otherwise, it is optimal not to exert effort. The payoff expected by the firm before the agent receives the information to be transmitted to the coordinator will therefore be

$$\Pi^P = \frac{1}{2}p\left[11 - 2 - \left(\frac{1}{2}2 + \frac{1}{2}10\right)\right] + \left(1 - \frac{1}{2}p\right)0,$$

that is,

$$\Pi^P = \frac{3p}{2} > 0.$$

2.3 Decentralized information

When information is decentralized, no agent communicates the signal she receives and they both make the effort decision according to the following rule prescribed ex ante by the coordinator: an agent that receives a null signal does not exert effort, whereas an agent that receives a perfect signal exerts effort if and only if the effort cost is revealed to be equal to 2. From an ex-ante perspective, an agent anticipates exerting effort whenever she observes a perfect signal that happens to reveal an effort cost equal to 2, an event that has probability $p/2$. Therefore, there is probability $(p/2)^2$ that the firm gains $11 - 2 - 2$ because each agent's effort cost is 2 and effort is exerted by both. There is probability $(p/2)(1 - p/2) + (p/2)(1 - p/2)$ that any one of the agents exerts effort and the other does not, with the end result that the firm gains payoff $0 - 2$ in this case. In all the other cases, the agents exert no effort and the firm gains nothing.

Given the coordinator's instructions, the payoff expected by the firm before the agents receive their signals is then

$$\Pi^D = \left(\frac{p}{2}\right)^2 (11-2-2) + p\left(1-\frac{p}{2}\right)(0-2-0) + \left[1-\left(\frac{p}{2}\right)^2 - p\left(1-\frac{p}{2}\right)\right]0,$$

that is, $\Pi^D = p(11p-8)/4$. In order for the predetermined behavioral rule to be optimal, it must hold that $p \geq 8/11$; if $p < 8/11$, the optimal rule is that an agent exerts no effort regardless of the signal received, in which case the payoff equals 0. In a compact manner, one can therefore write out the expected payoff when information is decentralized as

$$\Pi^D = \max\left\{0, \frac{p(11p-8)}{4}\right\}.$$

2.4 Routine

Under a routinary decision-making process, signals received by agents are ignored, so they are prescribed not to exert effort, since this is the optimal behavior in the absence of information. In consequence, the firm's payoff equals $\Pi^R = 0$. This neglect of information implies that coordination is accomplished by completely forgoing adaptation to an uncertain environment.

3 The optimal design of information and communication channels

When information gathering and tranmission involve no costs, determining the optimal organizational form simply requires that the expected payoff of each alternative be compared. Clearly, it holds that

$$\Pi^C \geq \Pi^P \geq \Pi^D \geq \Pi^R = 0,$$

where the inequalities are always strict unless signals are completely uninformative (i.e., $p = 0$). If information collection and transmission (from the agents to the coordinator and vice versa) were costless, the optimal organizational form would be complete centralization, followed by partial centralization, decentralization and finally one based on routines.

A complete centralization achieves a coordinated adaptation to a volatile environment and dominates partial centralization because information is better aggregated to minimize the likelihood of mistakes. Under partial centralization, coordination is preserved but mistakes are more frequent, so adaptation is worse. Under decentralization, there is some adaptation to the uncertain environment, but miscoordination is possible and agents are less likely to behave efficiently, and in fact sometimes they may act inefficiently relative to partial centralization, which explains why the latter is preferred. Finally, an organizational form based on routinary decision-making acts in an entirely predictable way, achieving coordination by completely forgoing adaptation to a volatile environment. However, not responding to uncertainty is costly in terms of forgone profits in expected terms, which explains why it is the least preferred.

3.1 Optimal organizational form with information costs

The analysis thus far has ignored the costs of obtaining and communicating information, so let us assume from now on that transmitting each signal to the coordinator involves a cost $t \geq 0$ (this cost could represent delays in decision-making), whereas gathering a signal requires an agent to incur cost $g \geq 0$. Optimal behavior by the firm requires that signals that are not going to be used should not be collected (and therefore transmitted). Taking this aspect into account, we can identify the subset of parameters for which each organizational form is preferred by the firm.

In order for complete centralization to arise as the optimal organizational form, it should hold that

$$\Pi^C - 2(g+t) = \frac{p(12-5p)}{4} - 2(g+t) \geq \Pi^P - (g+t) = \frac{3p}{2} - (g+t),$$

$$\Pi^C - 2(g+t) = \frac{p(12-5p)}{4} - 2(g+t) \geq \Pi^D - 2g = \max\left\{0, \frac{p(11p-8)}{4}\right\} - 2g,$$

and

$$\Pi^C - 2(g+t) = \frac{p(12-5p)}{4} - 2(g+t) \geq \Pi^R = 0.$$

Since $\Pi^C - 2(g+t) \geq \Pi^P - (g+t)$ is equivalent to $g+t \leq p(12-10p)/8$ and $\Pi^C - 2(g+t) \geq \Pi^R$ is equivalent to $r+t \leq p(12-5p)/8$, it holds that satisfaction of $\Pi^C - 2(g+t) \geq \Pi^P - (g+t)$ guarantees that $\Pi^C - 2(g+t) \geq \Pi^R$ is met. So optimal complete centralization requires that $g+t \leq p(12-10p)/8$, together with $\Pi^C - 2(g+t) \geq \Pi^D - 2g$. When $p \leq 8/11$, no other condition is required, since $\Pi^C - 2(g+t) \geq \Pi^R = 0 > \Pi^D - 2g$. When $p > 8/11$, $\Pi^C - 2(g+t) \geq \Pi^D - 2g$ is equivalent to $t \leq p(20-16p)/8$. The condition that $g+t \leq p(12-10p)/8$ implies that $t \leq g+t \leq p(12-10p)/8 \leq p(20-16p)/8$, so the condition that $\Pi^C - 2(g+t) \geq \Pi^D - 2g$ can also be ignored when $p > 8/11$.

Overall, it holds that partial centralization is the most tempting alternative to complete centralization, so the latter is the optimal organizational form if and only if $g+t \leq p(6-5p)/4$. Greater p makes complete centralization easier to sustain as an optimal outcome if and only if $p < 3/5$. The point is that the value of an extra signal to achieve better coordinated adaptation is positive for any $p > 0$, but the extra signal grows with signal quality if and only if such quality is not too large: the benefits of complete centralization grow with p but a decreasing rate (Π^C is strictly concave), whereas the benefits of the best alternative grow with p at a constant rate.

Partial centralization will be the optimal organizational form if and only if all the following conditions hold at the same time:

$$\Pi^P - (g+t) = \frac{3p}{2} - (g+t) \geq \Pi^C - 2(g+t) = \frac{p(12-5p)}{4} - 2(g+t),$$

$$\Pi^P - (g+t) = \frac{3p}{2} - (g+t) \geq \Pi^D - 2g = \max\left\{0, \frac{p(11p-8)}{4}\right\} - 2g,$$

and

$$\Pi^P - (g+t) = \frac{3p}{2} - (g+t) \geq \Pi^R = 0.$$

Clearly, the first and third inequalities can be rewritten as $p(6-5p)/4 \leq g+t \leq 3p/2$. The second one is relevant only if $p > 8/11$, in which case it can be written as $t - g \leq p(14 - 11p)/4$. In order for partial centralization to be the preferred organizational form, the unit cost of gathering and transmitting signals should be neither too small nor too large; when signals are precise enough, the difference between the cost of communicating a signal and collecting it should not be too large either: otherwise, a decentralized form would be preferred.

Turning to decentralization, optimality of this organizational form requires that $p > 8/11$. When this holds, it should also hold that

$$\Pi^D - 2g = \frac{p(11p-8)}{4} - 2g \geq \Pi^C - 2(g+t) = \frac{p(12-5p)}{4} - 2(g+t),$$

$$\Pi^D - 2g = \frac{p(11p-8)}{4} - 2g \geq \Pi^P - (g+t) = \frac{3p}{2} - (g+t),$$

and

$$\Pi^D - 2g = \frac{p(11p-8)}{4} - 2g \geq \Pi^C = 0.$$

The first condition is equivalent to $t \geq p(10-8p)/4$, whereas the second one is equivalent to $t \geq g + p(14-11p)/4$. Because $t \geq g + p(14-11p)/ \geq g + p(10 - 8p)/4 \geq p(10-8p)/4$, it holds that the first condition can be ignored, so we are left with $t - g \geq p(14-11p)/4$ and the third condition, which can be rewritten as $g \leq p(11p-8)/8$. Thus, decentralization requires that the cost of gathering a signal be low and that the difference between the cost of transmitting information and collecting it be large enough, besides coordination failures being too unlikely.

Finally, an organizational form based on routines is optimal when all the following requirements are met at the same time:

$$\Pi^C = 0 \geq \Pi^C - 2(g+t) = \frac{p(12-5p)}{4} - 2(g+t),$$

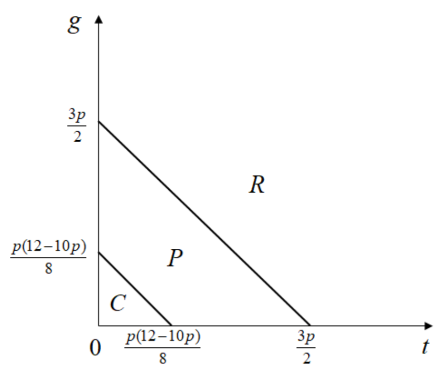
$$\Pi^C = 0 \geq \Pi^P - (g+t) = \frac{3p}{2} - (g+t),$$

and

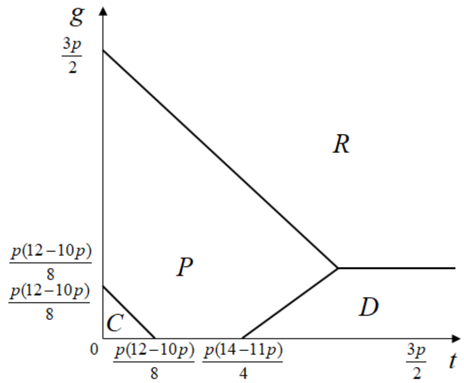
$$\Pi^C = 0 \geq \Pi^D - 2g = \frac{p(11p-8)}{4} - 2g.$$

The first inequality is equivalent to $g + t \geq p(12 - 5p)/8$, whereas the second one is equivalent to $g+t \geq 3p/2$. The fact that $3p/2 \geq p(12-5p)/8$ implies that the first inequality can be ignored, and only $g+t \geq 3p/2$ should be relevant. As for the third inequality, it directly holds when $p \leq 8/11$, whereas it requires $g \geq p(11p-8)/8$ when $p > 8/11$. When signals are not precise enough and decentralization is a negligible alternative, routines are preferred over any other form when the costs of collecting and transmitting information are high enough. If signals are sufficiently precise, routines must also dominate the decentralized organizational form, so the costs of collecting information inherent to the latter form should be high enough. It always holds that lower signal precision favors that the organization's actions do not adapt to the (uncertain) environment and the firm works in a routinary way.

The following figure represents graphically the values of g and t for which each organizational form is optimal when $p \leq 8/11$:



When $p > 8/11$, the situation is somewhat different, as illustrated by the following figure:


g
$\frac{3p}{2}$
R
$\frac{p(12-10p)}{8}$
P
$\frac{p(12-10p)}{8}$
D
C
0
$\frac{p(12-10p)}{8}$
$\frac{p(14-11p)}{4}$
$\frac{3p}{2}$
t