

Uncertainty Drives Them Apart - Managerial Practices in Teams

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Note: This paper was previously circulated as the second half of a broader paper titled “The First Time is Different: A Problem-Solving Approach to Innovation.” Following the suggestion of a discussant and seminar participants, I have developed the ideas below into a separate paper. This draft is the first version as a stand-alone paper. I continue to revise and clarify the insights of section 3. If a paper presentation is not possible, I would like to be considered for a poster presentation.

Abstract

Managerial practices vary not just across different organizational forms but also within. I present a model where some firms optimally choose the same organizational form, yet different managerial practices. Firms choose their organizational and managerial practices in response to a given task distribution. These distributions contain some relatively simple and some complex tasks. Some firms face distributions with low variance and low uncertainty about the tasks at hand, while other firms face distributions with high task uncertainty. I show that ‘team’ is the optimal organizational form for firms facing complex tasks, even if there is no uncertainty, and for firms facing high task uncertainty, even for relatively simple tasks. But optimal managerial practices depend on the distribution of tasks, the variance in pay-offs, and the likelihood that a particular worker’s effort is needed for the firm to succeed - and therefore complexity and uncertainty-driven teams choose different managerial practices. The results shed light on anecdotal variability of team management practices and suggest that empirical studies of team production take the underlying task distribution into account.

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1 Introduction

Firms vary in their organizational form as teams, flat or steep hierarchies as well as in their choice of managerial practices, such as how to allocate decision rights, how to incentivize workers, or how to codify language used at the firm. These managerial practices and the organizational form often interact, one constraining the choice of the other. For example, Cremer et al. [2007] investigates how the optimal language interacts with and constraints communication in three different organizational forms. But managerial practices also vary within the same organizational form. For example, surgery teams have well-defined roles, codified language, and limited purchasing rights. In contrast, product development teams often have shared leadership, broad language, and a budget to spend on whatever they need to develop a better product. Yet, both groups of people work as a team.

In this paper, I offer an explanation for such variations in managerial practices among firms with the same organizational form. I propose that the characteristics of the task distribution that a firm faces can explain distinct managerial practices within one particular organizational form: teams. The key insight is that teams are an optimal organizational choice for both complex tasks and for tasks with high task uncertainty. But optimal managerial practices depend on the distribution of tasks, the variance in pay-offs, and the likelihood that a particular worker's effort is needed for the firm to succeed - and therefore different practices are optimal for complexity and uncertainty driven teams, respectively.

For example, we know that using a pay-for-performance contract, a firm needs to compensate risk-averse workers for variations in outcome that are not due to the worker's effort. This risk-premium will be higher for firms that face a wide range of potential tasks with varying revenue outcomes and may tend to zero for firms facing complex but certain tasks. Also, the worker's contributing to the solution to a certain but complex task are certain that their expertise is needed for the task at hand. In contrast, facing unknown problem with a potentially simple solution workers know that there is a high probability that their particular expertise may not be needed. Thus, the moral hazard of free-riding is a concern in the latter scenario, but not in the former one. Consequently, a firm facing high task uncertainty is more likely to adopt alternative performance measures or use weak incentives and put more effort into screening during the hiring process to attract intrinsically motivated workers.

The intuition for other managerial practices is similar: Investments into tools that facilitate task completion can be made ex-ante, before the firm draws a problem, or ex-post. If there are cost-savings from ex-ante investments, a firm will make these investments ex-ante for tasks that it frequently faces. If the tasks that a firm faces vary widely, then that firm may be better off with ex-post investment - only purchasing tools for the problems at hand. Consequently, a team facing a complex but certain problem does not need to be involved in the decision making process, but a team facing high task uncertainty needs to be involved - resulting in different allocation of decision rights in the two teams.

We see this distinction play out in the real-world. As extreme examples, compare a product-

development team, for example, at an industrial design and development firm such as IDEO, with a surgery team. Most tools that the surgery team uses, such as scalpel, knives, retractors, etc. - some of which are highly specialized instruments - were purchased long before the patient entered the hospital. In contrast, the product-development team may have post-it notes and duct tape at hand, but will need to purchase whatever else they may need. Some of their purchases may be specific, custom-made, while others may be fairly generic items, e.g., a collection of remote controls when developing a new hand-held device.

To capture the firm's organizational and managerial response to a given complex or uncertain task distribution, I follow Garicano and Rossi-Hansberg [2006], Kremer [1993], and others, and model a firm as the owner of a task or problem distribution.¹ The firm has to hire workers who possess human capital in the form of knowledge, skills, or experience in order to solve problems and to thus generate revenue. Such problem solving tasks are characterized by the skills needed to solve them. Different tasks may require different skill sets. Workers are bounded rational and each worker only has one unit of knowledge. There are complex problems that require many different units of knowledge to be solved, and simple problems that only require two units. The firm knows its distribution of problems, and thus may face a little or a lot uncertainty about the tasks it faces. For any particular task the firm does not know what exact skills are required to solve it until the task is successfully completed. The firm can attempt to solve a problem more than once.

I deviate from the previous literature by modeling knowledge, skill, and experience as discrete units. These discrete units can be thought of as discrete bundles of human capital often distinguished in the real world: a college degree, being a tax lawyer or a certified accountant, or having twelve years of executive experience, being a surgeon, an anesthesiologist, or a bike mechanic.² This approach makes the model slightly less tractable but it allows me to distinguish variations in task uncertainty and task complexity.

In the first half of the paper, I investigate the firm's organizational choice in response to its task distribution. I show that sometimes it is optimal for the firm to attempt all problems only once using a flat, single-layer organization, i.e., an all-knowing team of workers tackles all problems the firm draws from the distribution. In particular, I show that firms that faces a distribution with high task uncertainty or a distribution with high task complexity optimally organize as teams.

In the second half of the paper, I restrict attention to task distributions along a linear spectrum between a complex but certain task and a distribution of relative simple but highly uncertain tasks. All distributions along this spectrum are optimally addressed using teams. I analyze the firm's managerial choices in response to its task distribution. I look

¹Throughout the paper I use the terms "problems" and "tasks" interchangeably.

²Typically, knowledge is modeled as a continuous parameter, making the firm's optimization problem tractable. But restrictions need to be placed on what knowledge workers can have and on the probability distribution of problems. For example, Garicano and Rossi-Hansberg [2006] assume that knowledge of different workers is nested and that the probability distribution decreases exponentially in the complexity of problems. Kremer [1993], Becker and Murphy [1992] assume that knowledge of different workers is disjoint and (implicitly) that the same highly complex problem occurs every period.

in turn at stylized models of contracts, decision rights, and optimal language. I show that firms facing high task uncertainty are more likely to be subject to free-riding problems and thus more likely to rely on relational contracts, are more likely to share decision rights with workers, and are more likely to use broad words to communicate than firms facing high task complexity, but limited task uncertainty - even though both kinds of firms optimally choose the same organizational structure.

The paper provides a link from the organizational literature to the empirical team production literature. The empirical literature on team production spans disciplines from medicine over psychology and sociology to economics, management, and operation science. The latter has considered firm, industry, and individual characteristics to understand when team production is beneficial, see DeVaro and Kurtulus [2006] for a review. However, with the exception of Boning et al. [2003], problem characteristics have mostly been ignored. This paper suggests that problem characteristics may indeed be one of the crucial determinants of the benefits of team productions. Moreover, results of this paper imply that the benefits of managerial choices, such as group incentives or shared decision making, for a team's productivity are likely dependent on the firm's underlying task distribution. Thus, when empirically investigating the relationship between these choices and productivity, the underlying distribution needs to be taken into account.

The remainder of the paper is structured as follows: Section 2 introduces the model, builds intuition using a numeric example, and establishes teams as the optimal organizational form for complex and uncertain task distributions. Section 3 adds to model to study a firm's managerial choices and establishes how firms facing high task uncertainty and high task complexity, respectively, optimally choose different managerial practices. Section 4 shows that the differences between complexity and uncertainty driven teams capture anecdotal differences of real-world teams. Finally, section 5 concludes the paper.

2 The Baseline Model of Tasks and Team Prevalence

In this section I build the baseline model of a problem solving firm. I show that teams are the optimal organizational response to both complex tasks and to tasks with high task uncertainty.

2.1 Problem Solving and The Firm's Organizational Choice

A firm is the owner of a distribution of problems³. Revenue is generated by solving these problems. In order to do so the firm hires workers who possess knowledge. The firm chooses which workers to employ, which workers should work collaboratively, i.e., jointly on the same problems, and who should report to whom, thus allowing hierarchies to arise. The firm also chooses which managerial practices adopt. That is, how to incentivize workers, whom to

³Throughout the paper I use the terms "tasks" and "problems" interchangeably.

assign decision rights, and how workers should communicate. I postpone a discussion of these managerial practices to section 3.

There are N units of knowledge, expertise, or skill in this economy. Knowledge is learned and used in discrete units, labeled A , B , C , and so forth. This captures a real-world coarseness, where knowledge, skill, or expertise are often described by discrete labels such as “two years of college education”, having a “law degree”, or being an expert in “building security”. It is such bundles that I have in mind when discussing “units of knowledge”. The coarseness and interpretation of these units depends on the context of the example.

Workers possess knowledge, but due to bounded cognitive capability, each worker is limited to one unit of knowledge. Workers can combine their expertise by working together as a team. For example, if one worker knows A and another worker knows B then jointly they provide $\{A, B\}$. The cost of hiring workers is denoted c_A , c_B , and so forth depending on the knowledge the worker has. The firm only pays workers for periods in which they work for the firm, i.e., periods in which the workers attempt to solve a problem for the firm.⁴ Abstracting away from coordination cost or synergies that may be gained, I assume that the cost of hiring multiple workers is linear, i.e., hiring a worker with knowledge A and one with knowledge B to work together in a team would cost $c_A + c_B$.⁵

The firm uses the workers’ knowledge to solve tasks. Tasks require a combination of knowledge and are labeled accordingly. For example, $t = ab$ is the task that requires knowledge A and B , and $t = abcd$ denotes the task that requires A , B , C , and D to be solved. I put aside any concerns that having “too much” knowledge may impede solving a problem, and assume that workers whose knowledge contains the minimally necessary knowledge can solve the problem. For example, a team with the knowledge set $\{A, B, C, D\}$ can solve $abcd$ but also ab , bc , cd , and ad .

A task is solved when workers who attempt solving the task have the necessary knowledge to solve it.⁶ For any given problem, the firm generally does not know what knowledge is needed to solve the task until the task is solved. Attempting to solve a problem takes workers one period. Problems may be attempted more than once. I assume that failing to solve particular problem does not reveal information beyond the observation that workers with this particular knowledge set are not able to solve the problem. For example, if an worker with knowledge $\{A\}$ fails to solve a problem he does not learn whether the problem is of type bc or ab . This stark simplification serves the purpose of conceptually separating solving a problem from diagnosing it.

The firm knows the probability p_t with which each possible task t occurs. It chooses its optimal organizational form in response to given labor market wages and the distribution

⁴This is consistent with a spot labor market, with allowing part time work, or with firms owning sufficiently many urns of the same distribution so that integer constraints do not bind.

⁵For sufficiently high coordination cost, it will not be optimal to address a distribution with high task uncertainty with a team. However, the paper’s key insight that managerial practices can differ within one organizational form is not affected.

⁶I abstract away from the cognitive processes of actually finding a solution.

of tasks it faces. I will say a task is more *complex* if it requires more units of knowledge to solve. Also, a firm faces a *higher task uncertainty* if there is more uncertainty about which knowledge is required to solve a given problem.⁷

If a problem is solved, revenue is generated. The revenue depends on the type of problem t that was solved and is denoted by v_t . For simplicity, I assume that all problems are valuable enough to be solved, i.e., $v_t > c_{\{1, \dots, N\}}$, where $\{1, \dots, N\}$ is the all-encompassing knowledge. This assumption allows me to focus on the optimal organizational form and the firm's optimal managerial practices rather than on the question of whether the firm produces at all. There is no depreciation over time in the value generated by solving a problem.

The firm's optimization problem is to choose in which order $\mathcal{K}_1 \rightarrow \mathcal{K}_2 \rightarrow \mathcal{K}_3 \rightarrow \dots \rightarrow \mathcal{K}_l$ which workers with knowledge \mathcal{K}_i should attempt to solve problems drawn from the distribution p_t in order to maximize profits. Any problems not solved by the worker(s) with knowledge \mathcal{K}_i are then attempted by worker(s) with knowledge \mathcal{K}_{i+1} . Any task that remains unsolved after workers with knowledge \mathcal{K}_l have attempted to solve it is discarded. Note that each knowledge set \mathcal{K}_i will be addressing fewer problems than the previous one. Therefore such a sequence has a natural interpretation as an l -layered hierarchy. I call a solution to this optimization problem *organizational form*.

I consider a partial equilibrium model. In other words, I assume that workers are endowed with particular knowledge, that firms face equilibrium wages, and no individual firm's hiring decisions affect these wages. Each firm is exogenously assigned their urn or distribution. There is no entry.

The timing for the firm's choice of organizational form and ensuing production is as follows.

⁷To define the uncertainty as the variance of the task distribution, we need to be able to "add" tasks, i.e., compute expressions like $\frac{1}{2}a + \frac{1}{2}ab$. One way to implement this is to consider the simplex in \mathbb{R}^{2^N-1} if there are N units of knowledge and assign each task to a vertex in the simplex. For example, if there are only $N = 2$ units of knowledge, the simplex in \mathbb{R}^3 is spanned by $(1, 0, 0)$, $(0, 1, 0)$, and $(0, 0, 1)$. Each of the three possible tasks a , b , and ab , can be assigned to one of these vertices. The uniform distribution $1/3(a, b, ab)$ has the expected value $1/3(1, 1, 1)$ and a variance of $2/3$.

Time Period	Event
T = 1	Firm learns its problem distribution.
T = 2	Firm chooses its organizational form.
T = 3	The firm hires appropriate workers.
T = 4	Production takes place:
T = 4.1	The firm draws a problem, workers solve the problem they are facing if they can, passing on or disregarding those they can't.
⋮	The firm draws a problem, workers solve the problem they are facing if they can, passing on or disregarding those they can't.

Revenue is generated in each of these sub-periods, and profits are realized.

In section 3, I will overlay and discuss the firm's choice of managerial practices.

2.2 A Specific Example: $N = 3$

To build some intuition, let us consider the specific case of $N = 3$.⁸ There are three units of knowledge A , B , and C , and six potential problems a , b , c , ab , ac , bc , and abc . For simplicity, I ignore the single-unit problems a , b , and c , and only consider the four problems of complexity greater or equal than two.⁹

A firm's task distribution is characterized by a probability quadruple $(p_{ab}, p_{ac}, p_{bc}, p_{abc})$. The set of all possible probability distributions form a 3-dimensional simplex in \mathbb{R}^4 . Addressing a problem drawn from a distribution $(p_{ab}, p_{ac}, p_{bc}, p_{abc})$, the firm has to choose in which order which workers should attempt to solve the problem first, second, and so forth. For example, the distribution $(.9, 0, 0, .1)$ is optimally addressed by a two-layered organization $AB \rightarrow ABC$, where first an A worker and a B worker jointly attempt to solve the problem. If they fail to do so, a team of three workers with knowledge ABC will address the problem.

In this example, there are 16 different organizational forms. Six of them are unique up to symmetry in the knowledge set of the first layer. Table 1 lists these six, together with their cost structure. All of these organizational forms solve all tasks the firm faces and generate the revenue $V = p_{ab}v_{ab} + p_{bc}v_{bc} + p_{ac}v_{ac} + p_{abc}v_{abc}$.

Comparing the different cost structures we see immediately, that the distribution of the

⁸The case for $N = 2$ does not offer a large enough variety of problems. In particular, for the argument to work I need to distinguish relatively simple problems that require two units of knowledge or expertise to be solved from complex problems that require all N units. The case where $N = 3$ is the smallest one where this distinction is meaningful.

⁹In the following, I want to emphasize the distinction between task-uncertainty and complex tasks by considering a distribution over relative simple tasks of constant complexity. That complexity needs to be at least two, so that there are combinatorial returns to knowledge and a team is optimal. The argument would work as well by considering a distribution over all $2^N - 1$ tasks or all tasks of complexity less or equal to some k .

Organizational Form	Cost
All-knowing 3-worker Team: ABC	c_{ABC}
Two-layer hierarchy: $AB \rightarrow ABC$	$c_{AB} + (1 - p_{ab})(c_A + c_B + c_C)$
Three-layer hierarchy $AB \rightarrow AC \rightarrow ABC$	$c_A + c_B + (1 - p_{ab})(c_A + c_C) + (1 - p_{ab} - p_{ac})(c_A + c_B + c_C)$
$AB \rightarrow BC \rightarrow ABC$	$c_A + c_B + (1 - p_{ab})(c_B + c_C) + (1 - p_{ab} - p_{bc})(c_A + c_B + c_C)$
Four-layer hierarchy: $AB \rightarrow AC \rightarrow BC \rightarrow ABC$	$c_{AB} + (1 - p_{ab})c_{AC} + (1 - p_{ab} - p_{ac})c_{BC} + (1 - p_{ab} - p_{ac} - p_{bc})c_{ABC}$
$AB \rightarrow BC \rightarrow AC \rightarrow ABC$	$c_{AB} + (1 - p_{ab})c_{BC} + (1 - p_{ab} - p_{bc})c_{AC} + (1 - p_{ab} - p_{ac} - p_{bc})c_{ABC}$

Table 1: This table shows six potentially optimal organizational forms for $N = 3$ that are unique up to symmetry in the first layer knowledge set. All organizational forms solve all problems and generate the same revenue $V = p_{ab}v_{ab} + p_{bc}v_{bc} + p_{ac}v_{ac} + p_{abc}v_{abc}$ for a problem distribution $(p_{ab}, p_{ac}, p_{bc}, p_{abc})$.

complex problem $(0, 0, 0, 1)$ is optimally addressed by a three-worker team. We also find that the distribution where all simple problems occur with equal probability $(1/3, 1/3, 1/3, 0)$ is also addressed by a three-worker team. Indeed, figure 1 shows the optimal organizational form for the face of the simplex where $p_{abc} = 0$.

The intuition behind a three-worker team, rather than a multi-layer hierarchy being optimal in the center of the distribution space shown, is that no smaller knowledge set is useful “enough” to first attempt to solve problems: a two-worker team with knowledge AB could only solve one third of all problems. In this case, adding another unit of knowledge triples the number of problems that can be solved. Combinatorial complementarity translates into economic complementarity.

One might suspect that team formation at the center of the distribution space is due to “synergy.” But if synergy were the sole driver then we would expect teams to be singular optimal in the middle range of each of the three edges, too. For example, a firm addressing the distribution $(p_{ac} = 2/3, p_{bc} = 1/3, p_{ab} = 0)$, could capture “synergy” by using a team providing all three units of knowledge rather than paying for four units of knowledge one third of the time. But it is not optimal for the firm to do so.¹⁰ In other words, ‘synergy’ alone cannot explain the optimality of teams at the center of the distribution space.

Thus, we find that both the complex problem (with no task uncertainty) and the task

¹⁰If the cost of knowledge is linear in the number of units of knowledge, then the expected cost of ABC is $3c$. But the expected cost of $AC \rightarrow BC$ is only $2c + (1 - p_{ac}) \cdot 2c = 22/3c < 3c$.

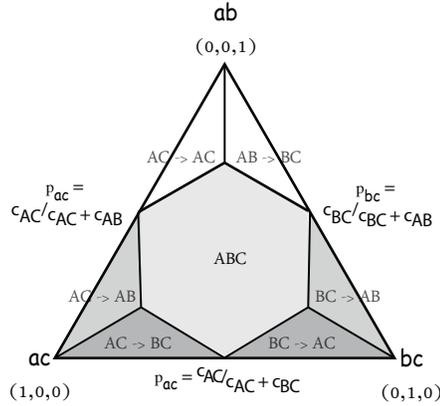


Figure 1: In a distribution space spanned by the three problems ab , bc , and ac all problems have the same complexity. But distributions with high task uncertainty at the center of the distribution space are optimally addressed by a team providing knowledge ABC . The figure drawn here assumes the cost of knowledge is linear in the number of units of knowledge.

distribution with high task uncertainty (and only simple problems) are optimally addressed by a team. Lemma 2 below shows that the region in which any organizational form is optimal is convex. Therefore, all task distributions of the form $(p/3, p/3, p/3, 1 - p)$ are optimally addressed by a three-worker team.

2.3 Complexity- and Uncertainty Driven Teams

The intuition developed for $N = 3$ carries over to the general case as long as the cost of hiring various workers does not vary too much.

Proposition 1 Assume that the cost for workers is not too varied. In particular, assume that $\max_{i=1 \dots N} w_i \leq 2 \min_{i=1 \dots N} w_i$, then firms facing either

- a. the single-problem distribution for the most complex problem, i.e., $p_{abcd \dots} = 1$ and $p_t = 0$ for all other t , or
- b. a uniform distribution of tasks with constant complexity $k \geq 2$

optimally organize as an all-knowing N -worker team or do not produce at all.

The first part of this result is tautologically true - no other knowledge set can solve the most complex problem. Since the firm knows that this is the only problem it faces, it will either employ workers who jointly provide all knowledge in the economy or not produce at all. For the second part of the proposition I show that the all-knowing team is cheaper than any knowledge sequence of length bigger than one that ends in the complete knowledge set.

In that case, however, complexity is not the driver of the organizational choice: Instead, no smaller knowledge set is useful “enough” to first attempt to solve problems. The share of tasks that workers with a smaller knowledge set could solve is too small to make it optimal for the firm.¹¹In other words, even absent variations of complexity and absent any complex problems the firms might face, sufficient uncertainty about the expertise required to solve a task results in single-layer flat organizational structure.

Thus, I have shown that both complexity (absent of any uncertainty) and uncertainty (absent of any complexity) can drive team formation.

Last but not least, the linearity of the pay-off structure implies:

Lemma 2 The region in the distribution space where a particular organizational form is optimal is convex.

Therefore, all distributions on the line from the vertex $(0, 0, \dots, N)$ to the center of the face of all problems of complexity 2 are optimally addressed by teams:

Proposition 3 Assume that there are only tasks of complexity 2 and tasks of complexity N . Assume that the cost for workers is not too varied. In particular, assume that $\max_{i=1\dots N} w_i \leq 2 \min_{i=1\dots N} w_i$. Denote

$$S = \binom{N}{2} = \frac{N}{N-1} 2$$

the number of tasks of complexity 2. Then firms addressing a distribution of the form

$$\text{Prob}(t) = \begin{cases} \theta/S & \text{if } t \text{ is a task of complexity 2} \\ 1 - \theta & \text{if } t \text{ is a task of complexity } N \end{cases} \quad \text{for } \theta \in [0, 1]$$

optimally organize as an all-knowing N -worker team or do not produce at all.

Note that as θ varies from zero to one, the distribution varies from a distribution of a single certain complex task ($\theta = 0$) to a distribution of many, equally likely relatively simple tasks ($\theta = 1$). Both of these distributions and all of them inbetween are optimally addressed using an N -worker team. Other distributions in the distribution space are also optimally addressed by an all-knowing N -worker team, but restricting distributions to this line is sufficient to understand a wide variation in managerial practices.

¹¹One may be tempted to draw a connection to the convex returns to knowledge - after all, a constant marginal increase in the cost of a larger knowledge sets yields an increasing return in term of the tasks that can be solved. However, the relationship is not as straight forward, since the remainder distribution after a first few attempts to solve a task may well be concave, thus making a multi-stage organizational form optimal. Convexity is necessary but not sufficient. A sufficient condition for the all-knowing flat organizational structure to be optimal is as follows: If for every knowledge set \mathcal{K} with $|\mathcal{K}| = k$ and every (sub)collection \mathcal{U} of tasks solvable by \mathcal{K}

$$\begin{aligned} & \text{Prob}(t \in \mathcal{U}) \cdot (N - k) \\ \leq & \text{Prob}(t \text{ strictly more complex than some } t' \in \mathcal{U} \text{ and } t \notin \mathcal{U}) \cdot k. \end{aligned}$$

3 Managerial Practices in Complexity- and Uncertainty-Driven Teams

In this section I study the management of workers in firms facing high task complexity and high task uncertainty, respectively. In the management of a firm, economists are most often concerned with (1) investment decisions and decision rights, (2) incentives and the structure of contracts, and (3) communication. Each of these three aspects is affected by the task distribution the firm faces.

In each of the following subsections I impose additional modeling assumptions in order to capture the interaction between the task distribution and the managerial choices the firm makes. It may seem at times that the set-up is too stylized or that assumptions do not apply equally well to firms facing task uncertainty and task complexity. The main objective of this section is to show that firms facing high task uncertainty make different managerial choices from those facing high task complexity. Identical assumptions that appear more suited for one type of firm than for the other underline the difference between the firms.

Some of the managerial choices, such as decision rights, are driven by the likelihood of individual tasks. Others, such as the optimal language depend on the variance of the tasks. Performance measures, in turn, depend on the variance in the generated revenue and on the likelihood of workers successfully free-riding. All of these vary along the line described in the previous section as

$$\text{Prob}(t) = \begin{cases} \theta/S & \text{if } t \text{ is a task of complexity } 2 \\ 1 - \theta & \text{if } t \text{ is a task of complexity } N \end{cases} \quad \text{for } \theta \in [0, 1].$$

Figure 2 summarizes how the various parameters change with θ .

3.1 Investments and Decision Rights

Consider a scenario where a firm can increase the value of a solution (or reduce the cost) by investing in tools or training, for example, a particular software package, machine, or exposure to particular methodologies. Some of these investments are general in nature as they are valuable for a wide range of tasks. Other investments are task specific in that they are only valuable for a particular task. Moreover, the decision to make such an investment can be made ex-ante, before facing any particular problem, or ex-post, after having gained some information about the task at hand. If the investment decision is made ex-post, then either the workers who address the problem must have decision rights to make the investment or they must communicate what they have learned to a decision maker. I assume that for the firm to make reasonable ex-post decisions it needs to set-up appropriate communication channels or establish hiring practices such that employed workers can be endowed with decision rights. In either case, the firm needs to pay a fixed cost $F \geq 0$ to implement ex-post decision making. If the investment decision is made ex-ante, no information beyond

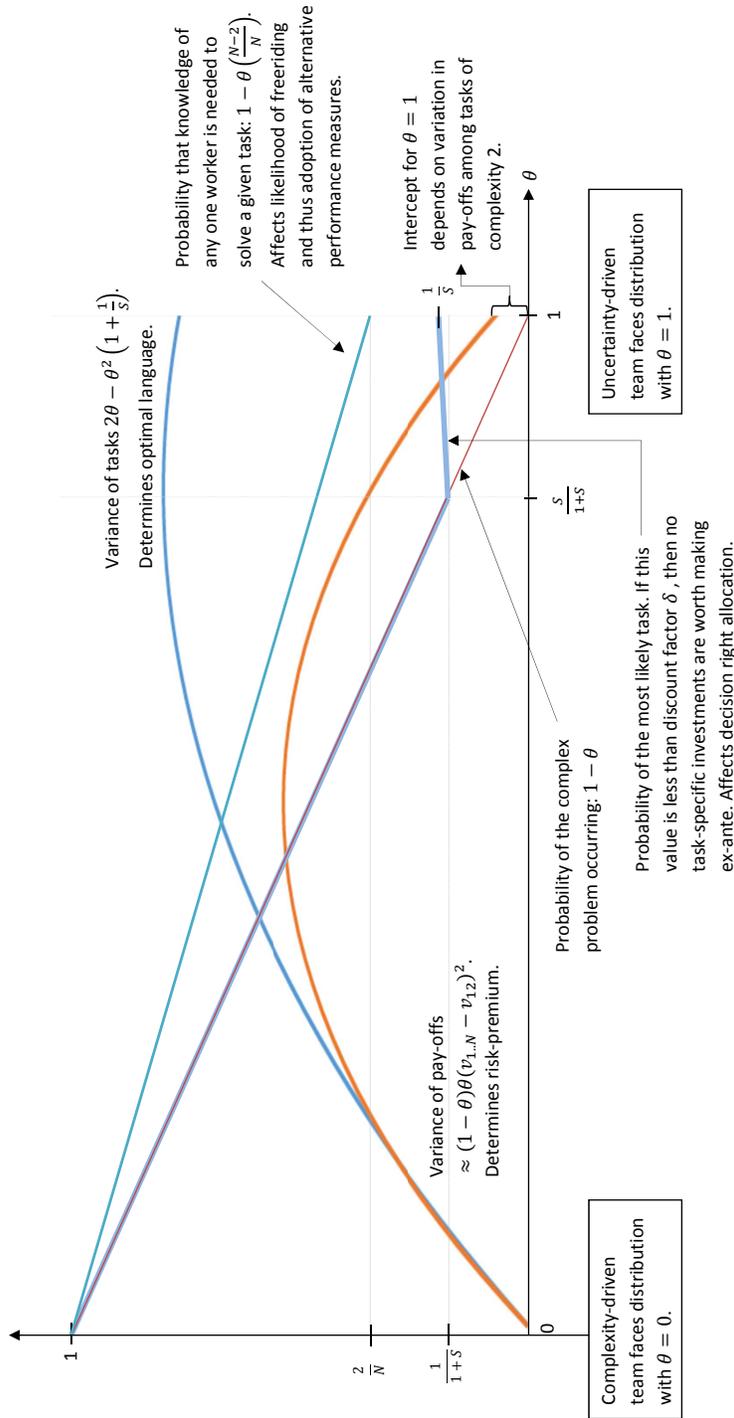


Figure 2: As θ varies from 0 to 1 the distribution varies from a distribution of a single certain complex task ($\theta = 0$) to a distribution of many, equally likely relatively simple tasks ($\theta = 1$). Both of these distributions and all of them inbetween are optimally addressed using an N -worker team. But the underlying task distributions differ and result in different probabilities of tasks, likelihood that workers contribute to a particular solution, variance of tasks and pay-offs. These in turn cause different managerial practices to be optimal for different values of θ , i.e., for different teams.

the task distribution is available or needs to be communicated.

I assume that it is cheaper for the firm to make such investments ex-ante. The cost savings might reflect making the investment at an opportune moment, the firm having more time to negotiate or to find alternative suppliers.

Formally, assume for now that the fixed set-up cost for ex-post decision making is $F = 0$ and that the firm can choose from a menu of investments $(C_i, r_i(\mathbf{t}))$. Each such investment increases the revenue generated when problem \mathbf{t} is solved to $(1 + r(i, \mathbf{t})) \cdot v_{\mathbf{t}}$. An investment i *generic*, if $r_i(\mathbf{t})$ is independent of \mathbf{t} , and *specific* to a problem $\hat{\mathbf{t}}$ if $r_i(\mathbf{t}) = 0$ everywhere except for $\mathbf{t} = \hat{\mathbf{t}}$. If the firm makes investment i after a problem is drawn, the marginal cost are C_i . If investment i is made ex-ante, the marginal cost are δC_i , with $\delta < 1$. The discount of $1 - \delta$ may reflect a discount in bulk ordering or the value of being able to make the investment at an opportune moment. I assume that the firm only has to make this investment once per problem and that the benefit accrues independently of which agent addresses the problem.¹² I say that an investment i is *valuable* for problem \mathbf{t} if $r_i(\mathbf{t}) \cdot v_{\mathbf{t}} \geq C_i$.

The firm decides for each i whether or not to make the investment. For each investment it makes, the firm also chooses between investing ex-ante and investing ex-post. If the firm makes the investment ex-post, the benefit is

$$\sum_{\mathbf{t} \text{ s.t. } i \text{ is valuable}} p_{\mathbf{t}} [r_i(\mathbf{t}) \cdot v_{\mathbf{t}} - C_i].$$

If the firm makes the investment ex-ant, the benefit to the firm is

$$\left[\sum_{\mathbf{t} \text{ s.t. } i \text{ is valuable}} p_{\mathbf{t}} r_i(\mathbf{t}) \cdot v_{\mathbf{t}} \right] - \delta \cdot C_i.$$

The benefit of investing ex-post is that the investment is only made for problems for which the investment is valuable. If this benefit exceeds the higher ex-post investment cost, then the firm invests ex-post. Formally, if the firm invests in i , the investment is made ex-ante if

$$\left[\sum_{\mathbf{t} \text{ s.t. } i \text{ is valuable}} p_{\mathbf{t}} r_i(\mathbf{t}) \cdot v_{\mathbf{t}} \right] - \delta \cdot C_i > \sum_{\mathbf{t} \text{ s.t. } i \text{ is valuable}} p_{\mathbf{t}} [r_i(\mathbf{t}) \cdot v_{\mathbf{t}} - C_i].$$

So the investment i is made ex-ante rather than ex-post

$$\delta \cdot C_i < C_i \cdot \sum_{\mathbf{t} \text{ s.t. } i \text{ is valuable}} p_{\mathbf{t}}.$$

which is equivalent to

$$(1 - \delta) > 1 - \sum_{\mathbf{t} \text{ s.t. } i \text{ is valuable}} p_{\mathbf{t}}.$$

The left hand side in this last inequality represents the savings that arise from making the investment ex-ante. The right-hand side reflects savings from not making unnecessary

¹²For the purpose of this discussion, it is useful to assume that the investment decision does not interact with the optimal organizational form. But I believe that this interaction is important in practice and may be a fruitful direction for future research.

investments. Naturally, a firm prefers an ex-ante over an ex-post timing of investment i if the corresponding savings are larger.

We summarize this finding in the following proposition:

Proposition 4 Assume $\delta < 1$. If an investment i is made, then the investment i is made ex-ante if and only if

$$\delta \leq \sum_{\mathfrak{t} \text{ s.t. } i \text{ is valuable}} p_{\mathfrak{t}}.$$

If a valuable investment i is specific to problem \mathfrak{t} , then the investment is made ex-ante if and only if the probability of problem \mathfrak{t} satisfies $p_{\mathfrak{t}} \geq \delta$.

The result is somewhat obvious, but it highlights the importance of the task distribution for the timing of investments. In particular, the proposition implies that (1) generic investments that are valuable for all problems are always made ex-ante, that (2) task-specific investments for frequent tasks are made ex-ante, and that (3) task-specific investments for rare tasks are made ex-post.

Now return to the specific setting where a firm faces the task distribution (p_a, p_b, p_{ab}) as before, and assume that the firm has the choice of three task-specific investments $(C_a, r_a), (C_b, r_b), (C_{ab}, r_{ab})$, respectively. Each of these investment will increase the value of the solving a corresponding task \mathfrak{t} to $r_{\mathfrak{t}} \cdot v_{\mathfrak{t}}$ at cost $C_{\mathfrak{t}}$. Assume that all three investments are valuable, i.e., $r_{\mathfrak{t}} \cdot v_{\mathfrak{t}} > C_{\mathfrak{t}}$.

Then the firm prefers an ex-ante investment over an ex-post investment if and only if $\delta < p_{\mathfrak{t}}$. Figure 3 a) shows the regions in the distribution space for which a firm will make ex-ante investments for the most frequently occurring task (shown for $\delta < 0.5$). Whether or not a firm makes further ex-ante investments depends on the organizational structure of the firm: For a flat organizational structure, the firm will make the ex-ante investment for another task \mathfrak{t}' if that task satisfies $p_{\mathfrak{t}'} > \delta$ as well. Figure 3 a) shows such distributions in the intersection of two shaded regions. For a hierarchy, a second level worker (or team) faces a residual distribution, e.g., if an A -worker solved all a problems, the firm's next layer faces the distribution $(0, p_b/(1 - p_a), p_{ab}/(1 - p_a))$. The firm will make an ex-ante investment for problems solved by the second layer if and only if it would have made one for a first-layer worker addressing the residual distribution. Recall that we can find residual distributions on the opposite edge of the solved problem's vertex. We can thus deduce the ex-ante investments made for higher layers of hierarchies. These investments are shown in figure 3 b).

As long as the fixed set-up cost for ex-post decision making is $F = 0$, all investments not made ex-ante are made ex-post. If $F > 0$, ex-post investments depend on the task distribution the firm faces.

Assume that paying the set-up cost is worthwhile for all task distributions if no task-specific investment is made ex-ante, i.e.,

$$p_a (r_a v_a - C_a) + p_b (r_b v_b - C_b) + p_{ab} (r_{ab} v_{ab} - C_{ab}) > F > 0.$$

If the firm does not make any ex-ante investments, i.e., $p_a < \delta$, $p_b < \delta$, and $p_{ab} < \delta$, then the firm will invest in infrastructure to make ex-post investments. For example, in figure 3 a) all firms facing a distribution in the white triangle in the middle of the simplex will invest in the infrastructure and make all task-specific investments ex-post.

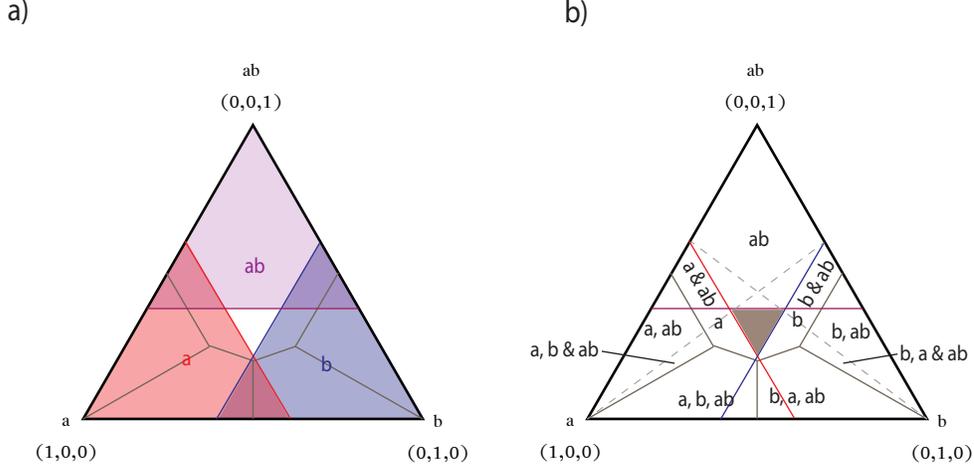


Figure 3: Assume all task-specific investments are valuable. a) The shaded regions in the simplex indicate the regions where an ex-ante investment in the respective task-specific tool or training is optimal. For the white area at the center of the simplex no task occurs frequently enough to warrant an ex-ante task-specific investment. In the specific case shown, the discount cost of the ex-ante investment are δC_t with $\delta < 0.5$. As δ increases, the regions where ex-ante investments are optimal decline in size. In particular, for $\delta > 0.5$ the colored regions would not overlap. b) Taking the optimal organizational form into account, we show all ex-ante task-specific investments. Small letters indicate the corresponding investments. Commas separate investments made for different layers of a hierarchy, ampersands indicated more than one task-specific investment is made. For hierarchical structures the investments corresponding to a layer's task(s) is made ex-ante if the task occurs frequently enough in the respective residual distribution. Firms facing distributions where no ex-ante investment is efficient will make all investments ex-post. The corresponding distributions are shaded grey. For sufficiently high set-up cost F only those firms will make ex-post investments.

Firms that optimally make some ex-ante investments may or may not find it worthwhile to invest in an ex-post decision making infrastructure. For example, if the firm optimally invests in (C_a, r_a) ex-ante, the firm will invest in the set-up cost for ex-post decision making if and only if

$$p_b (r_b v_b - C_b) + p_{ab} (r_{ab} v_{ab} - C_{ab}) > F.$$

In particular, the more frequently one or more problems occur in the firm's task distribution,

the less likely the firm is to invest in ex-post decision making.

Depending on the magnitude of F , the region in the simplex where firms make ex-post investments may extend to all investments not made ex-ante or only to those distributions where no ex-ante investments are made. Figure 3 b) shows which task-specific investments are made ex-ante, ex-post, or not at all taking the firm's optimal organizational structure as given.

To summarize, firms that face high task uncertainty distributions and therefore choose a flat organizational structure are more likely to engage in ex-post investments, share decision rights and/or have a more extensive communication structure than firms that choose a flat organizational structure because they face a task distribution with frequent complex problems.

3.2 Incentives and the Structure of Contracts

Assume that effort is costly for workers to provide and that the firm needs to either incentivize workers through performance-based contracts or invest in an infrastructure that ensures high input levels of effort. Such an infrastructure may involve explicit monitoring, extended hiring processes to ensure only intrinsically motivated individuals are hired, or investments in reputation to sustain relational contracts. In all of these cases, the cost associated with the practice is independent of the problem distribution the firm faces. Let F be the fixed cost investment the firm must make to ensure high (efficient) levels of effort are provided by its workers.

In contrast, implementing performance-based contracts does not require an infrastructure beyond the ability to observe the outcome each period and an enforcement mechanism. However, performance based contracts may be costly if hiring risk-averse workers requires the payment of a risk premium or if the performance pay has an overall damped impact effort.

I argue that the cost associated with performance-based contracts are higher for firms facing distributions with high task uncertainty, making them thus more likely to be the ones to adopt input-bases evaluations.

For specificity assume that firms face task distributions (p_a, p_b, p_{ab}) as before and performance-based contracts offered to worker i takes the form $(w_a^i, w_b^i, w_{ab}^i, w_0)$ where w_t^i denotes the wage paid to worker i if after the problem has been solved the problem turns out to have been task t . The wage w_0 is paid if the problem is not solved. I normalize the worker's utility such that $U(w_0) = 0$. The probability P_t that a worker with the appropriate expertise solves a problem t depends on the effort the worker exerts. Let f_A be the effort provided by an A-worker and f_B be the effort provided by a B-worker, and let $C_i(f_i) = 1/2f_i^2$ be the cost of effort. Given a particular contract, an A-worker working alone chooses which effort

to exert to maximize expected utility

$$\max_{f_A} p_a P_A(f_A) U(w_a^A) - \frac{1}{2} f_A^2$$

and an A -worker working together with a B -worker chooses which effort to exert to maximize expected utility

$$\max_{f_A} p_a P_A(f_A) U(w_a^A) + p_b P_B(f_B) U(w_b^A) + (1 - p_a - p_b) P_{ab}(f_A, f_B) U(w_{ab}^A) - \frac{1}{2} f_A^2.$$

I limit the following discussion to the organizational structure where an A -worker and a B -worker work together. The corresponding optimization problem exhibits both the risk-exposure and the damping of performance pay on the worker's effort. Both channels make performance-based pay less effective for firms facing high uncertainty distributions:

3.2.1 Risk Premium Depends on Task Distribution

Given a particular contract (w_a^A, w_b^A, w_{ab}^A) and equilibrium effort levels f_A^* and f_B^* , an A -worker's expected pay-off is

$$E[U(w^A)] = p_a P_A(f_A^*) U(w_a^A) + p_b P_B(f_B^*) U(w_b^A) + (1 - p_a - p_b) P_{ab}(f_A^*, f_B^*) U(w_{ab}^A) - \frac{1}{2} f_A^{*2}.$$

Assume that the cost of effort is low enough such that each worker exerts sufficient effort to solve every problem he has the expertise to solve, i.e., $P_A(f_A^*) = P_B(f_B^*) = P_{ab}(f_A^*, f_B^*) = 1$. If the worker is risk-averse, the wages will reflect a risk-premium reflecting the variance in pay the worker is subject to. Given a particular distribution the firm faces (p_a, p_b, p_{ab}) the worker is exposed to the variance in pay equal to

$$\begin{aligned} Var(w^A) &= w_a^{A2} p_a (1 - p_a) + w_b^{A2} p_b (1 - p_b) + w_{ab}^{A2} (1 - p_a - p_b) (p_a + p_b) \\ &\quad - 2w_a^A w_b^A p_a p_b - 2w_a^A w_{ab}^A p_a (1 - p_a - p_b) - 2w_b^A w_{ab}^A p_b (1 - p_a - p_b) \end{aligned}$$

Paying an A -worker when the solved problem turns out to have been a b problem reduces the variance in pay that the A worker is exposed to but it has no impact on the worker's effort provision. In particular, observe

$$\begin{aligned} \frac{dVar}{dw_b^A} &= 2w_b^A p_b (1 - p_b) - 2w_a^A p_a p_b - 2w_{ab}^A p_b (1 - p_a - p_b) \\ &= 2p_b (w_b^A - p_b w_b^A - p_a w_a^A - p_{ab} w_{ab}^A) \\ &= 2p_b (w_b^A - \bar{w}^A) \end{aligned}$$

where \bar{w}^A denotes the average pay the A -worker expects as well as the average pay the firm expects to spend. We see that the variance in pay will decrease as w_b^A increases as long as $w_b^A < \bar{w}^A$. Moreover, the difference between $w_b^A - \bar{w}^A$ is more salient the more frequently

problem b occurs. In other words, the larger p_b the more expensive it is to incentivize a risk-averse A -worker. Figure 4 shows the distributions where it is most expensive to incentivize risk-averse A -worker and B -worker, respectively. Note that for larger values of p_b the A -worker does not need to be incentivized (in the first layer of the organization) due to the hierarchical structure optimally chosen for larger values of p_b .

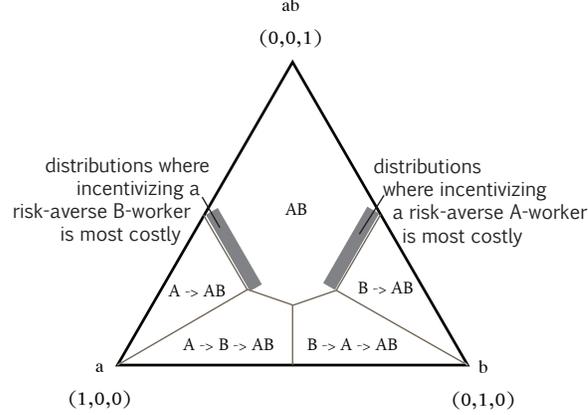


Figure 4: Worker i is offered a contract of the form (w_a^i, w_b^i, w_{ab}^i) . Paying an A -worker when the solved problem turns out to have been a b problem reduces the variance in pay that the A worker is exposed to but it has no impact on the worker's effort provision. The gray areas mark the distributions where it is most expensive to incentivize risk-averse A -worker and B -worker, respectively. Note that for larger values of p_b the A -worker does not need to be incentivized (in the first layer of the organization) due to the hierarchical structure optimally chosen for larger values of p_b .

As a consequence, firms facing distributions in the center of the simplex face relative high cost of both incentivizing A - and B -workers.

3.2.2 Impact on Effort Depends on Task Distribution

Now, in turn let us focus on the optimal effort provided. Assume utility is linear, i.e.

$$U_i(w_i^i) = w_i^i$$

and assume that the probability of solving a problem given f_A is exponential, i.e.,

$$P_A(f_A) = 1 - e^{-f_A} \quad P_B(f_B) = 1 - e^{-f_B} \quad P_{AB}(f_A, f_B) = \sqrt{(1 - e^{-f_A})(1 - e^{-f_B})}$$

The probability P_{AB} is normalized to the same magnitude as P_A .

Then the A -worker's optimization problem simplifies to

$$\max_{f_A} p_a P_A(f_A) w_a^A + p_b P_B(f_B) w_b^A + (1 - p_a - p_b) P_{ab}(f_A, f_B) w_{ab}^A - \frac{1}{2} f_A^2$$

The first-order-condition of this optimization problem is

$$f_A = p_a P'_A w_a^A + (1 - p_a - p_b) P'_{ab} w_{ab}^A.$$

We can rewrite the first-order condition as

$$\mathcal{F} = p_a w_a^A + (1 - p_a - p_b) \cdot \frac{\sqrt{(1 - e^{-f_B})}}{\sqrt{(1 - e^{-f_A})}} w_{ab}^A - f_A e^{f_A}.$$

Observe that keeping effort levels of the B level worker fixed, the best effort response of the A -worker to a given level of effort f_B of the B -worker decreases in p_b :

$$\begin{aligned} \frac{\partial f_A}{\partial p_b} &= - \frac{\frac{\partial \mathcal{F}}{\partial p_b}}{\frac{\partial \mathcal{F}}{\partial f_A}} \\ &= \frac{\frac{\sqrt{(1 - e^{-f_B})}}{\sqrt{(1 - e^{-f_A})}} w_{ab}^A}{-0.5(1 - p_a - p_b) \cdot \frac{\sqrt{(1 - e^{-f_B})}}{(1 - e^{-f_A})^{3/2}} \cdot e^{f_A} w_{ab}^A - e^{f_A} - f_A e^{f_A}} \\ &< 0 \end{aligned}$$

The B -worker faces an analogous optimization problem. The two workers' respective first order conditions implicitly define best response functions

$$\begin{aligned} f_A e^{f_A} &= p_a w_a^A + (1 - p_a - p_b) \cdot \frac{\sqrt{(1 - e^{-f_B})}}{\sqrt{(1 - e^{-f_A})}} w_{ab}^A \\ f_B e^{f_B} &= p_b w_b^B + (1 - p_a - p_b) \cdot \frac{\sqrt{(1 - e^{-f_A})}}{\sqrt{(1 - e^{-f_B})}} w_{ab}^A \end{aligned}$$

based on which we can numerically determine the equilibrium effort levels provided.

Figure 5 b) shows the equilibrium effort provided by an A -level worker for different distributions, keeping the contracts (w_a^A, w_b^A, w_{ab}^A) and (w_a^B, w_b^B, w_{ab}^B) fixed. We see that indeed the equilibrium effort of the A -worker decreases in probability p_b . In contrast, panel a) shows the equilibrium effort provided by an A -level worker who is working alone and whose effort can only affect the solution of a problems. Observe that for a A -worker who works alone the equilibrium effort increases in p_a . Given the firm's task distribution and the equilibrium effort provided by A - and B -workers but ignoring the firm's organizational structure, panel c) shows iso-profit lines across the distribution space, with profit increasing toward the ab vertex. In panel d) the boundaries of optimal organizational forms are overlaid. we see that in particular firms that optimally organize in a flat organizational structures due to high task uncertainty reap less benefits from performance-based contracts than firms that optimally organize in a flat organizational structures due to high task complexity.

3.3 Communication

Finally, consider communication and the optimal language for firms facing high task uncertainty and high task complexity.

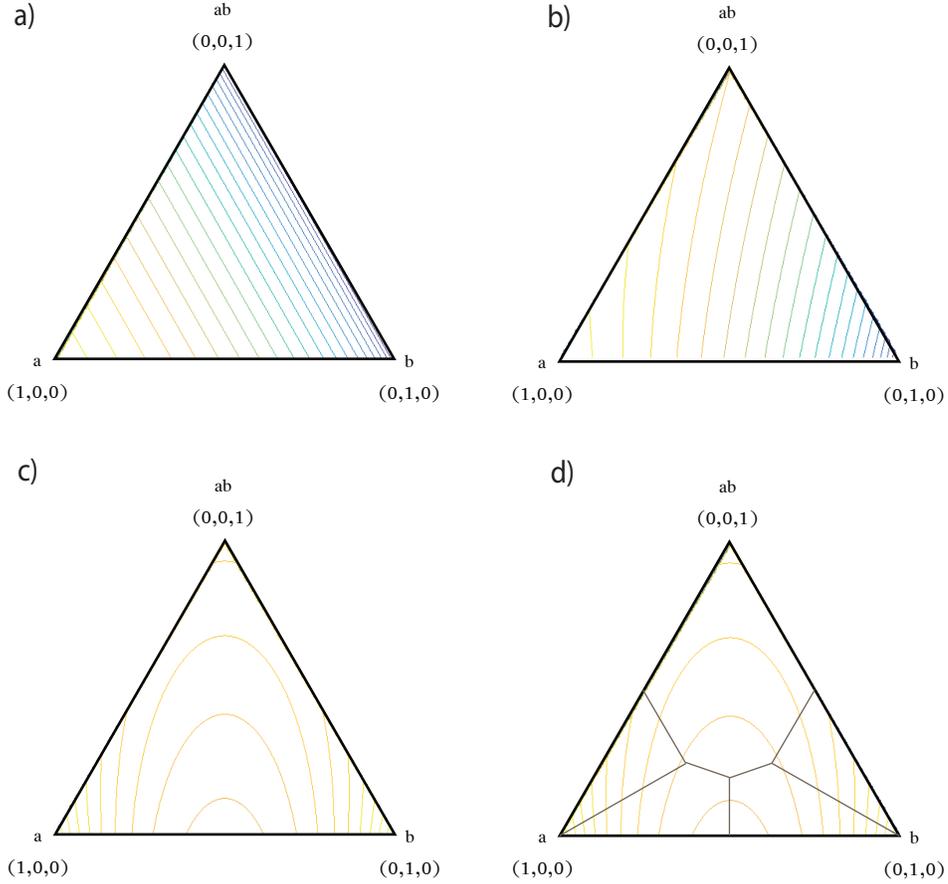


Figure 5: Worker i is offered a contract of the form (w_a^i, w_b^i, w_{ab}^i) . Panel a) shows iso-effort lines of an A -worker if that A -worker is working alone. Effort levels increase as p_a increases. Panel b) shows the iso-effort lines for an A -worker if the A -worker works jointly with a B -worker. Effort levels increase as p_b decreases. Panel c) shows iso-profit lines across the distribution space, with profit levels increasing toward the ab vertex. In panel d) the boundaries of optimal organizational forms are overlaid.

Cremer et al. [2007] formally model the optimal vocabulary in a team depending on the frequency with which the team encounters particular events. They consider a set of problems that members of a team need to communicate about. Since the team members are subject to bounded rationality, they can only learn a limited number of words. Therefore, more than one problem might optimally be assigned to the same word. Cremer et al. [2007] argue that the marginal benefit of an additional word is high at first and then decreasing for firms that face a narrow task distribution, i.e., one with a few problems occurring very frequently. In contrast, the marginal benefit of an additional word is constant or only slowly decreasing for a broad task distribution, i.e. one with many problems occurring infrequently. Consequently, the implication the task distribution has on the size of the optimal language is ambiguous.

However, given a fixed number of words to work with, the optimal language for a firm with a narrow distribution will always contain more words referring to a few number of events, while the optimal language for a firm with a wide distribution will mostly consist of words referring to a large number of events.

Applied to the setting of this paper, the optimal language for flat organizational structures due to high task complexity consists of words with narrow and specific meanings. In contrast, the optimal language for firms facing high task uncertainty will be more general and consist of words with broad meaning.

As an unexplored consequence, firms with complexity-driven teams may be more easily able “codify” the necessary language, since it is more specific and narrow. For example, the firm may be able to write down a relevant “vocabulary” list for an *A* worker. The firm may hence be easily able to substitute one “A”-worker with another “A”-worker. However, within uncertainty-driven teams, the language is likely to be more fluid and history-dependent, e.g., “This part of the problem looks similar to the problem we worked on two periods ago.” In that case, changing team-members would result in a (partial) loss of the language developed.

4 Managing Real-World Teams facing High Task Uncertainty and High Task Complexity

To summarize the previous subsections, compared to a complexity driven team an uncertainty driven team is expected to be more communication intensive, communicate using broader words, rely on less high-powered incentives, have more decision rights, less task-specific tools and training, be less likely to be monitored, and use reputation or other alternative mechanisms to overcome free-riding problems.

As a case study I here contrast a surgery team and a team working at the industrial design company IDEO. Figure 6 shows a surgery team and a team at IDEO at work.¹³ Whereas

¹³Sources: a) The Pediatric Cardiac Surgery Inquest Report, Chpt. 3, http://www.pediatriccardiacinquest.mb.ca/ch03/diagram3_2.html, Palestine Children Relief Fund, <http://www.pcrf.org/>

the former consist of prescribed number of nurses, anesthesiologist, surgeon, and assistants with specific responsibilities, the latter consist of "four to eight people with different skill sets and experiences" and no particular roles.

The comparison between the complexity-driven surgery team and the uncertainty-driven IDEO team shows many differences between these teams. The surgery team uses a precise, narrow language to conduct an operation, while the IDEO team does not employ any specialized language. Roles and responsibilities are clearly prescribed for the members of the surgery team but vary or are undetermined for the IDEO team. Almost all of the equipment and tools the surgery team uses during the procedure were purchased by the hospital before the patient was even admitted. In contrast, IDEO relies on generic tools such as "Sharpie markers, giant Post-its for the walls, and rolls of old-fashioned butcher-shop paper on the tables" as well as "foam core, blocks, tubing, [and] duct tape" for their project work and purchase additional items as needed after a project has started. These differences align with the different managerial choice we expect based on the discussion of the previous subsections - even though both surgery and brainstorming at IDEO is done in "teams."

5 Conclusion

Using a model of discrete units of knowledge this paper develops a model of the firm as problem solving. I show that firms facing distributions with high task complexity and those facing distributions with high task uncertainty optimally choose the same flat non-hierarchical organizational structure - all-knowing N -worker teams. But the two firms fill choose different contract structures, will adopt different decision rights, and implement different languages. Although not discussed in this paper, I expect that similarly optimal leadership and culture are different for complexity and uncertainty driven teams.

I believe that the distinction between complexity- and uncertainty-driven teams is meaningful in the real world and is, for example, reflected in the apparently contradictory advice given on "how to build a better team." Recommendations range from setting clear leadership, defining clear role expectations, and hiring "for competency first" to distributing leadership, flexible role assignments, and hiring "for character first." While the former set of suggestions seem more appropriate for complexity-driven teams, the latter set appears more suited for uncertainty-driven teams.

The results in this paper are consistent with teams being the optimal organizational form to perform a hip replacement surgery (complex and predictable) as well as develop a new product with certain specifications (unknown solution). But the paper also suggests that the management of teams should be matched to the underlying task distribution.

palestinernote.com/cfs-filesystemfile.ashx/___key/CommunityServer.Blogs.Components.WeblogFiles/news/0576.Steve-Sosebee-_2D00_-Italian-doctors-1.jpg.
b) <http://blog.gentry.io/ideo-seen-through-a-leica-m3>.

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