Incentives and the Nature of Uncertainty

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Work in Progress. All comments and feedback are welcome.

1 Introduction

Firms face many uncertainties - about the future price of a commodity, the success of a new product, or the ability of a worker the firm hires. To understand the impact such uncertainties have on firms' decision making, uncertainty is typically modeled as a perturbation of the outcome given a "best effort" input. This approach is attractive: It applies to many different situations, the "best effort" input assumption seems reasonable, and the models are tractable. This approach can explain how agents share risk (Arrow (1970); Borch (1962)), why agent receive low-powered incentives when multitasking (Holmstrom and Milgrom (1991)), how the dynamics of a "rat race" arises when workers' types are unknown and beliefs are updated based on observable outcomes which also depend on effort (Holmstrom (1999)), and how incentives for innovation differ from incentives for routine activities (Ederer (2008)).

Some stylized facts, however, are not consistent with this "one-approach-fits-all" modeling of uncertainty. For example, agricultural producers can choose to purchase crop insurance, but even companies with a good track record do not usually have access to insurance covering a failed product launch. Manufacturing firms often emphasize a "get it right the first time" policy, while some pharmaceutical companies establish a culture that "makes it safe to fail" (Goffee and Jones (2007)). Although many contracts exhibit more risk sharing when uncertainty increases, some contracts shift the risk completely from the agent to the principal as uncertainty increases. For example, Bajari and Tadelis (2001) show contracts from construction projects shift from "fixed price" to "cost plus" as the uncertainty about the appropriate design increases.

Each of these observations can be explained separately. For example, the industry has long-term experiences with crop and weather variability, whereas there is naturally little information or experience available for any new product. The quality of researchers at

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pharmaceutical companies may be less uncertain than that of employees at a manufacturing plant, because they are more thoroughly screened, their degrees and backgrounds may be more credible signals for their quality, thus allowing the company to have a supportive culture. Finally, uncertainty about the appropriate design in construction projects also increases the value of decision rights to change the design and thus the hassle of renegotiations. In other words, the change in contracts may be the result of a trade-off between increasing ex-ante incentives and lowering ex-post transaction costs (Bajari and Tadelis (2001)).

In this paper I propose that the distinction between value uncertainty and input uncertainty can jointly explain these stylized facts. Value uncertainty is uncertainty about the value that is generated from a known best input. For example, a farmer may know what the best time is to plant a corn crop in the Spring, where to get the best seeds and fertilizer, etc. But given this “best effort”, there is still a large uncertainty about how much the crop is worth after harvest, because of world-wide trading of corn. In contrast, input uncertainty refers to uncertainty about what inputs are necessary to generate a particular value. For example, deployed U.S. soldiers frequently suffer long-term consequences from medical conditions that could be avoided through treatment in any hospital, because they are far away from the next hospital, on-site treatment possibilities are very limited, and prompt evacuation is often not feasible. As a consequence, there is a known demand and high value generated from any product that would mitigate this problem. Such products may take the form of better portable treatment possibilities, portable or remote diagnostic tools, or better protective gear. What is unknown is what technology and what expertise is needed to create such a product.

It is true that conditional on some particular “best effort” to provide appropriate inputs, a firm facing input uncertainty will face an uncertainty about the overall outcome. In the above examples, the probability distribution that a new generation product generates a high profit may be similar to that of the farmer’s profit, given the farmer’s and the firm’s best efforts. Similarly, given best efforts, the probability that a sudden demand shock will lead to larger profits for the manufacturing plant may be the same as the probability that the development efforts of a pharmaceutical company are successful. Not knowing what the value of a newly-build condominium building will be upon its completion may result in the same ex-ante profit probability distribution as not knowing the contingencies and cost that will arise before a new high-profile museum is completed.

Thus it may seem that conditional on a “best effort,” there is no meaningful distinction between value and input uncertainty. However, this view obfuscates that the firm has an influence over the choice of inputs while perturbations to the value generated are usually exogenous. As a consequence, firms act differently to determine the “best effort” to put forward, and they respond differently to a failed effort depending on whether they face value or input uncertainty.

In the above examples, the farmer has little control over the local weather, production levels in Brazil, and demand for corn in China. However, the company has a choice how much to invest in research and development before launching a new product. Manufacturing firms typically know what is the “right thing to do,” even though there may be uncertainty about the value of the goods produced. If no large profit is realized, the firm can update their demand forecasting, but will not necessarily change the production process. In contrast, a pharmaceutical company may know the value of and demand for a product, but faces a tremendous uncertainty about how to produce such a product. If no large profit is realized, the pharmaceutical company can learn from a failure, change the product’s composition, bring other expertise on board. Finally, an experienced condominium-developer will have little uncertainty about how to build the condominiums most suited for the particular spot and generated the highest realized profit - even if he does not know what that profit will be. The contractors he uses and the work process will differ little from one development to the next. In contrast, building a high-profile museum, such as the Getty Museum in Los Angeles, may generate a known value, but organization of the construction and the hiring of contractors and experts will reflect the uncertainty about how the design has to be adapted throughout the construction process.

In this paper I explore the different implications that input and value uncertainty have on the choice a firm makes. I show that firms organize differently given their different ex-ante knowledge about the inputs needed for successful production, and that they write different sets of incentive contracts reflecting the distinct sources of outcome uncertainty. Finally I show that output reveals less information about a worker’s type in a firm facing input uncertainty than in a firm facing value uncertainty.

This work sits at the intersection of the study of uncertainty and organizational design. Others before have drawn attention to the different impact different kinds of uncertainty can have. For example, Weitzman (1974) shows how cost and benefit uncertainty drive whether prices or quantities are optimal control mechanism. However, this line of study does usually not distinguish between uncertainty that arises as an exogenous shock and uncertainty that the firm can mitigate: Both volatile prices of inputs required for production and uncertainty about the required technology can result in a cost uncertainty for a firm. In the latter case the firm can mitigate the uncertainty it is exposed to through experimentation, learning, hiring, and other organizational choices, in the former case it cannot. Endogenous uncertainty can arise when multiple players interact either inside a firm or within the whole economy, and, for example, prices are determined through aggregate demand and supply, e.g. Holt (1979); Kurz and Wu (1996). Agents then choose their demand or supply by taking into account their beliefs about the other players’ demand and supply choices. In contrast, this paper focuses on “internal” choice variables rather than market interactions, and uncertainty does not arise dynamically through the players’ actions. More closely related is the supply chain management study of uncertainty about when and how much of an input is be needed: The decision to hold an input in inventory or to procure it as needed is related to the decision whether to attempt a task with a large collection of expertise in the first attempt or to use a smaller collection and maintain the option of a second attempt in a hierarchy-like approach, Li and Kouvelis (1999). In this sense, if the worker receives a contract that is contingent on his expertise being used in the completion of a task, then the base wage w_0 corresponds to the inventory holding cost, whereas the contingent wage w_1 corresponds to the purchase cost of the input good. This parallel, however, does not extend to considering more than one input, as this paper does. If more than one input is required, then complementarity between the inputs can crucially affect the firm's optimization problems, as shown here.

Many seminal insights have emerged from studying the interaction between uncertainty and organizational design. However, all of these studies are limited to one kind of uncertainty or one organizational choice variable or both. For example, considering how the optimal contract a firm offers depends on exogenous shocks to observable outcomes, Arrow (1970); Borch (1962) show how agents share risk, Holmstrom and Milgrom (1991) argues why agents receive low-powered incentives when multitasking, and Holmstrom (1999) demonstrates how "rat race" dynamics arise when workers' types are unknown and beliefs are updated based on observable outcomes. Considering a one-dimensional uncertainty about which or how much input is required for production, Garicano (2000) shows that a firm optimally organizes as a hierarchy and how the number of layers and the span of control in the hierarchy depend on the distribution of tasks the firm faces. This is adapted and extended in the first essay of this dissertation, Bernhardt-Walther (2011), to show how the organizational form of hierarchies - and teams as degenerate hierarchies - depends more generally on multi-dimensional input uncertainty and task complexity. This paper builds on this work, and uses a slightly different set-up that allows us to analyze two kinds of uncertainty and multiple organizational choices and their respective interactions.

There is a third kind of uncertainty where inputs are chosen at different points in time and information about the optimal input choice becomes available between different input choices. In the literature, this is commonly modeled as either the firm being uncertain as to which input to choose, but a (local) agent can learn this information before making the appropriate choice, e.g., (Prendergast (2002)). Alternative, such uncertainty is interpreted as uncertainty about a future "state of the world", (e.g., Grossman and Hart (1986)). Such "state uncertainty" is an intermittent scenario in that the choice set of what the firm can affect through organizational choices is smaller than with pure input uncertainty but larger than with pure value uncertainty. I discuss how state uncertainty relates to the main model presented in this paper in section 4.2.

The main contribution of this paper, however, is to help bridge the gap between the theoretical literature on the organization for innovation on one hand and the concerns of practitioners and empirical observations on the other hand. The theoretical literature on organization for innovation has mostly focused on innovation as a contractual problem and has modeled it as a high variance event (conditional on best effort), see Holmstrom (1989); Manso (2007); Ederer (2008). But empirical and anecdotal evidence suggests that innovation differs from other activities a firm engages by exposing the firm to a different kind of uncertainty, rather than higher uncertainty, (Buxton (2007); Kelly and Littman (2000)). Moreover, contractual concerns are consistently outranked by organizational concerns as obstacles to innovation by the Senior Management Survey on Innovation, conducted annually by the Boston Consulting Group and Business Week Magazine since 2004. This paper takes a different approach to modeling innovation: Bill Buxton, a designer and a researcher at Microsoft, that "almost anyone who has actually built a product [...] will tell you that they really didn't know enough to start until they had finished."[1] In this spirit, input uncertainty considered in this paper is most meaningful interpreted in the context of innovation activity. Innovation means producing or doing something for the first time. There is a large uncertainty of how to produce it. This uncertainty is resolved subsequently in repeated reproduction through learning-by-doing. Thus, naturally, producing something for the first time involves different uncertainty than reproducing the same product thousands of times. This paper provides a framework to understand the different impact these different uncertainties have.

The paper is structured straightforward. Section 2 presents the baseline model. Section 3 adapts the baseline set-up to consider how a firm's organizational design, incentive-contracts, and the information revealed through output observation depend on input and value uncertainty, respectively. I discuss some extensions in section 4. Section 5 concludes.

2 The Model

Consider a world where the production output of a firm depends on the state of the world and the state of the world is described by $(\tau, \theta) \in \Theta$. The first part τ describes the part of the state known to the firm, the second part θ is unknown to the firm. If the state of the world is (τ, θ) and the firm utilizes the input vector $\mathbf{x} \in \mathbb{R}^n$, then the firm generates a profit of $\Pi(\mathbf{x}; \tau, \theta)$. The firm's general optimization problem is

$$\Pi^*(\tau) = \max_{\mathbf{x}} E_\theta \big[\Pi(\mathbf{x}; \tau, \theta)\big].$$

Typically, the firm does not care about the complete function $V(\mathbf{x}; \tau, \theta)$, but about the optimal input $\mathbf{x}^*(\tau)$ and the distribution of realizable profits of $\Pi(\mathbf{x}^*; \tau, \theta)$. Uncertainty about the state of the world can affect neither, either, or both of these quantities. I will speak of *value uncertainty* if the firm faces uncertainty about $\Pi^*(\mathbf{x}^*; \tau, \theta)$, and *input uncertainty* if the firm confronts uncertainty about $\mathbf{x}^*(\tau)$.

The distinction between input and value uncertainty may, at first sight, appear superfluous. Consider, for example, two firms that both use a single input $x \in \mathbb{R}$ in production $x \in \mathbb{R}$. The first firm faces a pure input uncertainty. Its optimal input x_θ is a random variable, and the profit generated from producing using x is given by

$$\Pi(x; \tau, \theta) = v_0 \cdot \delta(x, x_\theta),$$

where

$$\delta(x, x_\theta) = \begin{cases} 1 & \text{if } x = x_\theta \\ 0 & \text{else} \end{cases}.$$

[1] "Sketching User Experiences: Getting the design right and the right design", p.78

Assume that the firm's best effort $\hat{x}$ matches the optimal input x_θ with probability $p(\tau)$. Then the firm generates the value

$$\Pi(\tau) = \begin{cases} v_0 & \text{with probability } p(\tau) \\ 0 & \text{with probability } (1 - p(\tau)) \end{cases} .$$

In contrast, the second firm knows the optimal input x_0 but faces value uncertainty. The profit generated from producing using x is given by

$$\Pi(x; \tau, \theta) = v_0 \cdot \delta(x, x_0) + \epsilon_\theta,$$

where

$$\epsilon_\theta = \begin{cases} 0 & \text{with probability } p(\tau) \\ -v_0 & \text{else} \end{cases} .$$

In this case, the firm's "best effort" is always to choose $\hat{x} = x_0$ and the firm generates the value

$$\Pi(\tau) = \begin{cases} v_0 & \text{with probability } p(\tau) \\ 0 & \text{with probability } (1 - p(\tau)) \end{cases} .$$

In other words, conditional on providing a best-effort input, both firm's face the same value distribution.

This argument, however, obfuscates that the best-effort input is affected by many of the firm's organizational choices. For example, the second firm in the above example can write contracts with "complete instruction" to use x_0 as an input, whereas the first firm is constrained to inherently incomplete contracts and has to find a way to learn about the optimal input x_θ.

The central argument of this paper is that value and input uncertainty have different impact on the organization of a firm, including the contracts it writes, its ownership structure, and its optimal organizational form.

For specificity, I assume that there are two inputs[2] $a \in \{a_1, a_2\}$ and $b \in \{b_1, b_2\}$. The two inputs can represent capital and labor, ability and effort, or two different skills. With the exception of section 3.3, I assume that inputs are perfectly observable. For each of the two inputs there is an optimal input a_θ and b_θ which depends on the state of the world. The firm chooses input sets $\mathbf{A} :\subset \{a_1, a_2\}$ and $\mathcal{B} \subset \{b_1, b_2\}$. The overall profit generated from producing with inputs $\mathbf{A} :$ and $\mathcal{B}$ in a state (τ, θ) is given by

$$\Pi(\mathbf{A} :, \mathcal{B}; \tau, \theta) = v_0 \delta(\mathbf{A} :, a_\theta)\, \delta(\mathcal{B}, b_\theta) + \epsilon_\theta \;-\; C(\mathbf{A} :, \mathcal{B}),$$

where $C(\mathbf{A} :, \mathcal{B})$ describes the cost of using the input a and b,

$$\delta(\mathbf{A} :, a_\theta) = \begin{cases} 1 & \text{if } a_\theta \in \mathbf{A} : \\ 0 & \text{else} \end{cases} ,$$

[2]It will become clear in section 3.1 that considering one input would not suffice.

and $\delta(\mathcal{B}, b_\theta)$ is defined similarly. In other words, production is successful if and only if the firm provides the required inputs. The firm can provide excess inputs to ensure production is successful, but this is costly to do.

I assume that the state (τ, θ) affects the parameters of the profit function as follows

$$\begin{aligned} a_\theta &= \begin{cases} a_1 & \text{with probability } p_a(\tau) \\ a_2 & \text{else} \end{cases} \\ b_\theta &= \begin{cases} b_1 & \text{with probability } p_b(\tau) \\ b_2 & \text{else} \end{cases} \\ \epsilon_\theta &= \begin{cases} 0 & \text{with probability } p_H(\tau) \\ -v_0 & \text{else} \end{cases} . \end{aligned}$$

A firm that operates in state τ faces *higher input uncertainty* than a firm in state τ' if $Var(a_\theta, \tau) > Var(a_\theta, \tau')$ and $Var(b_\theta, \tau) > Var(b_\theta, \tau')$ or, equivalently, if

$$p_a(\tau) \cdot \big(1 - p_a(\tau)\big) \ > \ p_a(\tau') \cdot \big(1 - p_a(\tau')\big) \quad \text{and } p_b(\tau) \cdot \big(1 - p_b(\tau)\big) \ > \ p_b(\tau') \cdot \big(1 - p_b(\tau')\big).$$

Similarly, a firm facing state τ faces *higher value uncertainty* that a firm in state τ' if $Var(\epsilon_\theta, \tau) > Var(\epsilon_\theta, \tau')$ or, equivalently, if

$$p_H(\tau) \cdot \big(1 - p_H(\tau)\big) \ > \ p_H(\tau') \cdot \big(1 - p_H(\tau')\big).$$

Without loss of generality, I assume that $p_a \geq 1/2$ and $p_b \geq 1/2$ and that $p_a < p_b$.

3 The Impact of Uncertainty on the Organization of the Firm

Using the above set-up as a baseline, I adapt the assumptions to reflect various dimensions of the organization of the firm in turn.

3.1 Optimal Organizational Form

To first analyze the optimal organization of inputs for production I assume that all inputs have constant marginal cost c.

In the absence of input uncertainty, the firm knows the optimal input is $\mathbf{A} := \{a_1\}$ and $\mathcal{B} = \{b_1\}$, and it uses this and only this input in production. The profit generated by the firm facing value uncertainty is

$$\Pi_V(\{a_1\}, \{b_1\}; \theta, \tau) = v_0 + \epsilon_\theta \ - \ 2c.$$

The variance of the outcome reflects the binomial distribution of the perturbation term, and is given by

$$Var(\Pi_V) = p_H(\tau)\big(1 - p_H(\tau)\big)v_0^2.$$

The value v_0 here is generated through the use of a_1 and b_1. This can be interpreted as the firm providing, say, capital a_1 and hiring labor b_1, as hiring a contractor that provides both inputs, or as the firm instructing existing employees to use a_1 and b_1. In particular, it is also consistent both with the firm hiring two workers providing on of the inputs each and with the firm hiring one worker who provides both inputs. Crucially, only the task at hand determines which inputs are used and whether one or several workers are engaged for productions. In particular, the choice of inputs does not depend on the uncertainty, and the uncertainty the firm faces is unaffected by these choices.

In contrast, consider a firm that does face input uncertainty but no value uncertainty. The optimal use of inputs in production depends on whether the firm can attempt to provide the correct inputs multiple times. I consider here the more interesting case where the firm can repeatedly attempt to provide the correct inputs. I delegate the discussion of the case where the firm faces a one-shot game at providing the correct inputs in the appendix. The comparison with a firm facing value uncertainty is similar in both cases.

For simplicity, assume that the firm learns nothing about the required inputs through previous attempts and that its "guesses" are based on probabilities only. The firm chooses input sets for each attempt. In a fraction of the cases production will be successful. If production is not successful, then the firm provides the inputs according to the "next best guess." In other words, the firm chooses a sequence of input sets to try. Table 1 shows three possible sequences.

	1st attempt		2nd attempt		3rd attempt		4th attempt	
	A :	$\mathcal{B}$	**A** :	$\mathcal{B}$	**A** :	$\mathcal{B}$	**A** :	$\mathcal{B}$
1.	$\{a_1\}$	$\{b_1\}$	$\{a_2\}$	$\{b_1\}$	$\{a_1\}$	$\{b_2\}$	$\{a_2\}$	$\{b_2\}$
2.	$\{a_1, a_2\}$	$\{b_1\}$	$\{a_1\}$	$\{b_2\}$	$\{a_2\}$	$\{b_2\}$		
3.	$\{a_1, a_2\}$	$\{b_1, b_2\}$						

Table 1: If a firm facing input uncertainty can attempt to complete a task multiple times, then it will use different inputs for different attempts. This table shows examples for the sequence of input sets a firm might use in different attempts.

The first two sequences can be interpreted as sequential experimentation, where in the first attempt inputs are used "that usually work." If those inputs prove insufficient, then other inputs are tried. The last sequence can be interpreted as "throwing the kitchen sink in"-experimentation, where the firm provides all possible inputs at once. The first two sequences are also consistent with 'hierarchies' where different inputs from different attempts correspond to different expertises in different levels of the hierarchy. Every level attempts to solve tasks with the expertise available at this level. If the task cannot be addressed, it is passed to the next level of the hierarchy.

Among all such sequences, the firm chooses the one that maximizes expected profits given the state of the world τ. For the three sequences given in table 1 above, the expected profit is given in table 2.

	Expected Profit
1.	$\Pi_1 = v_0 - \left[2c + (1-p_a p_b)2c + (1-p_b)2c + (1-p_a)(1-p_b)2c\right]$
2.	$\Pi_2 = v_0 - \left[3c + (1-p_b)2c + (1-p_a)(1-p_b)2c\right]$
3.	$\Pi_3 = v_0 - \left[4c\right]$

Table 2: Expected profits for the input-sequences described in table 1.

It is useful to express the variance of these profit functions.

$$
\begin{aligned}
Var(\Pi_1) &= \Big[2p_b(2-p_b) + p_a(1-p_a)\Big] \cdot 4c^2 \\
Var(\Pi_2) &= \Big[2p_b(2-p_b) + p_a(1-p_a) - p_b\big(2p_b(1-p_a) + 2pa(1-p_a) + 2p_a(1-p_b) + p_a\big)\Big] \cdot 4c^2 \\
Var(\Pi_3) &= 0
\end{aligned}
$$

Note that the variance of the profit depends not only on the probabilities $(p_a(\tau), p_b(\tau))$, but also on the firm's organizational choice. In particular, for any fixed probability (p_a, p_b) it is true that $Var(\Pi_1) > Var(\Pi_2) > Var(\Pi_3)$. However, no unambiguous relationship exists to the variance $Var(\Pi_V)$, except for the obvious $Var(\Pi_V) \geq Var(\Pi_3)$.

Also note that for all three sequences production is eventually successful. While this is not necessarily true for the optimal sequence in general, I show in the appendix that if $v_0 > 4c$, then it is always optimal for the firm to organize in a manner that production is eventually successful. In this case, up to symmetry, the three sequences described in table 1 are the only potentially optimal ones. Figure 1 shows how the firm's optimal sequence depends on the probabilities (p_a, p_b) the firm faces. In particular, firms that face the highest input uncertainty, i.e., in the neighborhood of $(p_a, p_b) = (1/2, 1/2)$, optimally choose to provide all possible inputs at once. This is not because all inputs are always needed. Indeed, every input is needed only in about half of all cases; every input pair is only needed in about a quarter of the cases. Instead it is because every input pair is required so rarely that it is costly to attempt all production tasks with a sequence of input-attempts: Production would be unsuccessful for too many tasks. As a consequence, the output variance $VarP(\Pi)$ is smallest where the input uncertainty is highest.

To summarize, the particular optimal organizational form of providing input depends on the specific assumptions about whether the firm can attempt production multiple times, what the firm may learn from unsuccessful production, whether all production successes are equally valuable, and whether the marginal cost of inputs are constant. However, the key observations about the comparison with a firm that faces value uncertainty generalize: The

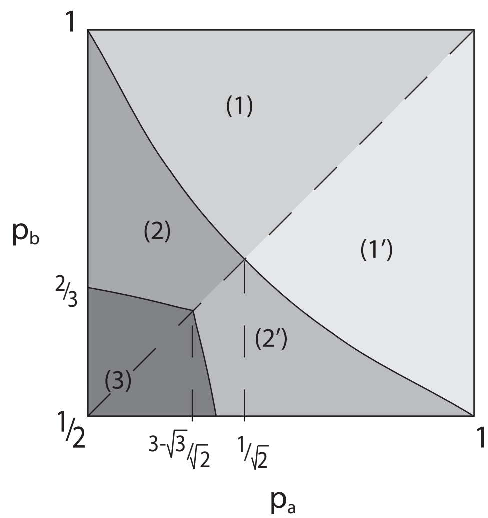

Figure 1: Depending on the probabilities (p_a, p_b) that a firm faces, any of the three organizational sequences shown in table 1 can be optimal. The areas marked (1), (2), and (3) denote the probabilities for which the firm optimally organizes its inputs according to the first, second, and third entry in table 1, respectively. In the areas marked (1') and (2'), the corresponding sequences for $p_a < p_b$ are optimal.

optimal organizational design is determined by input uncertainty rather than the specific task at hand. The uncertainty that a firm faces about the realized profit in turn depends on its choice of organizational design.

3.2 Contracts and Incentives

In this section, I assume that inputs are provided by workers. I consider the incentive-contracts a firm optimally uses for hiring workers.

3.2.1 Observable Inputs

Assume that each worker can provide two inputs of the form (a, b) with $a \in \{a_1, a_2\}$ and $b \in \{b_1, b_2\}$. The worker's type is publicly known. The worker has a certainty-equivalent reservation wage of w_E. The firm can offer the worker a contract that is contingent on a successful outcome, i.e., the worker is paid w_1 in case value v_0 is generated and w_0 otherwise. The worker's utility is denoted by u and the firm's utility by V with $u', V' > 0$ and $u'', V'' < 0$.

The worker's participation constraint is given by

$$Prob(\text{ success })u(w_1) - \Big(1 - Prob(\text{success})\Big)u(w_0) \geq u(w_E).$$

Moreover, the ratio $u'(w_1)/u'(w_0) \leq 1$ is a measure for the risk compensation the worker receives: The larger the fraction, the smaller the compensation.

I assume that the firm can observe which inputs were used ex-post. As before, consider first a firm that faces value uncertainty. Such a firm solves the optimization problem

$$max_{w_1,w_0}\; p_H V(v_0 - w_1) + (1 - p_H)V(-w_0)$$

subject to the constraint

$$p_H u(w_1) + (1 - p_H)u(w_0) \geq u(w_E).$$

The solution to this problem is a text-book example[3]. The optimal coinsurance contract between the firm and the worker satisfies

$$\frac{V'(v_0 - w_1)}{u(w_1)} = \lambda = \frac{V'(-w_0)}{u(w_0)} \tag{1}$$

where λ is the Lagrangian multiplier of the worker's participation constraint.

For a firm that faces input uncertainty, the optimization problem depends on the firm's organizational design. I showed in subsection 3.1 above that the variance of the output generated depends on the firm's organizational choice, with the firms facing the highest input

[3] Literally; see Bolton and Dewatripont (2005), p. 130ff.

uncertainty optimally choosing an organization that results in the lowest output variance. We may therefore expect that firms which face a higher input uncertainty and consequently lower output uncertainty, offer less risk compensation. But the relationship is not as straight forward and the drivers that determine the risk compensation are more subtle.

It is true in any case that a firm that chooses to approach each production task with a one-stage-sequence that provides all four inputs at once, as described in the third entry in table 1, offers no risk compensation at all.

Proposition 1 Firms that face high input uncertainty and optimally organize in a one-stage-sequence pay all workers their certainty equivalent wage w_E in all periods. This is true whether the contracts are contingent on an overall successful outcome or on an individual worker contributing to a successful outcome.

The general optimization problem is more complicated. Consider a firm that optimally organizes in four stages, hiring one worker for each of the four stages $k = 1, ..., 4$ as described by the first entry in table 1. Each worker is offered a contract contingent on the outcome at stage k, that is, a wage w_1^k is paid if production is successful at stage k and a wage w_0^k is paid otherwise. Let p_k denote the unconditional probability that a random production task is solved by the worker at stage k, and let $\tilde{p}_k$ denote the conditional probability that worker k can complete a random production task that he confronts, i.e.,

$$\begin{aligned} p_1 &= p_a p_b \\ p_2 &= (1-p_a)p_b \\ p_3 &= p_a(1-p_b) \\ p_4 &= (1-p_a)(1-p_b) \end{aligned} \qquad \begin{aligned} \tilde{p}_1 &= p_1, \\ \tilde{p}_2 &= \frac{p_2}{1-p_1}, \\ \tilde{p}_3 &= \frac{p_3}{1-p_1-p_2}, \quad \text{and} \\ \tilde{p}_4 &= \frac{p_4}{1-p_1-p_2-p_3} = 1. \end{aligned}$$

Then the firm's optimization problem is given by

$$\max_{w_1^k, w_0^k} \sum_{k=1}^{4} p_k \cdot V\left(v_0 - \sum_{i=1}^{k-1} w_0^i - w_1^k\right)$$

subject to the workers' participation constraints for $k = 1, ..., 4$

$$\tilde{p}_k u(w_1^k) + (1-\tilde{p}_k)u(w_0^k) \geq u(w_E). \tag{2}$$

Let λ_k be the Lagrangian multiplier for the kth participation constraint. Then the first order conditions with respect to $\left[w_1^k\right]$

$$0 = -p_k V'\left(v_0 - \sum_{i=1}^{k-1} w_0^i - w_1^k\right) + \lambda_k \tilde{p}_k u'(w_1^k)$$

and $\left[w_0^k\right]$

$$0 \;=\; -\sum_{i=k+1}^{4} p_i \cdot V'\left(v_0 - \sum_{j=1}^{i-1} w_0^j - w_1^i\right) \;-\; q \cdot V'\left(\sum_{i=1}^{4} w_0^i\right) \;+\; \lambda_k (1-\tilde{p}_k) u'(w_0^k)$$

imply that

$$\frac{\tilde{p}_k u'(w_1^k)}{(1-\tilde{p}_k)u'(w_0^k)} = \frac{p_k V'\left(v_0 - \sum_{i=1}^{k-1} w_0^i - w_1^k\right)}{\sum_{i=k+1}^{4} p_i \cdot V'\left(v_0 - \sum_{j=1}^{i-1} w_0^j - w_1^i\right)}$$

or equivalently,

$$\frac{u'(w_1^k)}{u'(w_0^k)} = \frac{V'\left(v_0 - \sum_{i=1}^{k-1} w_0^i - w_1^k\right)}{\frac{1}{\sum_{i=k+1}^{4} p_i} \sum_{i=k+1}^{4} p_i \cdot V'\left(v_0 - \sum_{j=1}^{i-1} w_0^j - w_1^i\right)} \tag{3}$$

Recall from equation (1) that the corresponding condition for a firm facing value uncertainty is given by

$$\frac{u'(w_1)}{u'(w_0)} \;=\; \frac{V'(v_0 - w_1)}{V'(-w_0)}. \tag{4}$$

Equation (3) and the participation constraints 2 exhibit various interactions that jointly determine the firm's equilibrium risk compensation. First, the conditional probability $\tilde{p}_k$ increases from $p_1 = p_a p_b$ at the first stage to 1 at the last stage. While $\tilde{p}_k$ does not necessarily increase from each step to the next, it does so for a wide range of probabilities p_a, p_b. As it increases, the worker's uncertainty about the wage he receives each period decreases, and the firm needs to compensate the worker less for accepting this uncertainty. Second, there is risk-smoothing between stages: The risk-averse firm can ensure a higher overall outcome if a problem is not solved at the first stage, if it accepts a lower outcome for the cases in which a task is completed at the first stage by offering a contract with a large spread $w_1^1 - w_0^1$. Finally, there is a continuation value after a failed attempt. As a consequence, failure generates the value v_0 minus the wages paid after failed attempts in previous stages. This value may be larger or smaller than zero. Similarly, the value of a success at any stage is v_0 reduced by the wages paid in previous attempts. In particular, if the value of a failed attempt never decreases below zero, then workers at a firm facing input uncertainty receive less risk compensation than workers at a firm facing value who would receive the same wages. In this case, the organizational design of the firm has an uncertainty-mitigating effect: Success in all but the first stage is never "as sweet" as success when facing value uncertainty, because it comes at the cost of pay wages to the workers in the previous stage(s). Conversely, failure at any but the last stage is never "as bitter", because production may still be successful at a later stage.

3.2.2 Unobservable Effort

Next, I consider how unobservable effort affects optimal contracts in firms facing value and input uncertainty, respectively.

To abstract away from team incentives and team moral hazards, I now assume that workers can provide any combination of inputs, though at different wages. The worker's type is publicly known. Worker have reservation wage of w_R. In addition, I now assume that workers have to invest effort e into production. I follow the standard set-up[4] and assume that conditional on providing the appropriate inputs the probability of successful production is given by $p(e)$ with $p(0) = 0$, $p(\infty) = 1$, and $p'(0) > 1$. I normalize the cost for the worker to provide effort e to e.

As before, the firm can offer the worker a contract that is contingent on a successful outcome, i.e., the worker is paid w_1 in case value v_0 is generated and w_0 otherwise. I now assume that both workers and the firm are risk-neutral, so that $u(w) = w$ and $V(\Pi) = \Pi$.

The new worker's participation constraint is given by

$$Prob(\text{ success })w_1 \; - \; \Big(1 - Prob(\text{success})\Big)w_0 \; - \; e \; \geq \; w_R.$$

A firm facing value uncertainty now optimizes

$$\max_{e,w_1,w_0} \; p(e)p_H(v_0 - w_1) \; + \; \big(1 - p(e)p_H\big)(-w_0)$$

subject to the constraints

$$p(e^*)p_H w_1 \; + \; \big(1 - p(e^*)p_H)\big)w_0 \; - \; e^* \geq w_R$$

and

$$e^* \in \text{argmax}_e p(e)p_H w_1 \; + \; \big(1 - p(e)p_H\big)w_0 - e.$$

So for any fixed wage levels w_1 and w_0, the value of the marginal effort to the firm is given by

$$MV(de; w_1, w_0) = p'(e)p_H(v_0 - w_1) \; - \; p'(e)p_H(-w_0) = p'(e)p_H\big[v_0 - (w_1 - w_0)\big]. \qquad (5)$$

Similarly, the marginal benefit to the agent is

$$MB(de; w_1, w_0) = p'(e)p_H w_1 \; - \; p'(e)p_H w_0 - 1 = p'(e)p_H\big[w_1 - w_0\big] - 1. \qquad (6)$$

For a firm that faces input uncertainty, the optimization problem is slightly more complicated. For example, if a problem can be attempted multiple times, it may be optimal for the firm to introduce redundancy in inputs such that a production task not completed at an earlier stage can still be completed at a later stage. I exclude this possibility from this discussion.

Consider, for example, the firm that optimally organizes in four stages as described in the first entry of table 1. Such a firm hires four workers $i = 1, ..., 4$ and optimizes the effort level e^i and wages w_1^i and w_0^i for each of the four workers. To simplify notation, let p_i denote

[4] See, for example, Bolton and Dewatripont (2005), p. 130.

the exogenous ex-ante probability that the ith worker has the appropriate inputs to solve a random production task, i.e.,

$$p_1 = p_a p_b, \;\; p_2 = (1-p_a)p_b, \;\; p_3 = p_a(1-p_b), \;\; \text{and } p_4 = (1-p_a)(1-p_b).$$

Moreover, let $\tilde{p}_i$ denote the conditional exogenous probability that worker i has the appropriate inputs to solve a production task he confronts, i.e.,

$$\begin{aligned}
\tilde{p}_1 &= p_1, \\
\tilde{p}_2 &= \frac{p_2}{1-p(e^1)p_1}, \\
\tilde{p}_3 &= \frac{p_3}{1-p(e^1)p_1 - p(e^2)p_2}, \quad \text{and} \\
\tilde{p}_4 &= \frac{p_4}{1-p(e^1)p_1 - p(e^2)p_2 - p(e^3)p_3}.
\end{aligned}$$

Note that if efforts are perfect, i.e., $p(e^i) = 1$, then $\tilde{p}_4 = 1$.

Then the firm's optimization problem is

$$\begin{aligned}
\max_{e^i, w_1^i, w_0^i} \quad & p(e^1)p_1(v_0 - w_1^1) \\
+ \quad & p(e^2)p_2(v_0 - w_0^1 - w_1^2) \\
+ \quad & p(e^3)p_3(v_0 - w_0^1 - w_0^2 - w_1^3) \\
+ \quad & p(e^4)p_4(v_0 - w_0^1 - w_0^2 - w_0^3 - w_1^4) \\
+ \quad & \big[\big(1 - p(e^1)big)p_1 \, + \, \big(1 - p(e^2)\big)p_2 \\
& + \big(1 - p(e^3)\big)p_3 \, + \, \big(1 - p(e^4)\big)p_4\big] \cdot (-w_0^1 - w_0^2 - w_0^3 - w_0^4)
\end{aligned}$$

subject to the eight participation constraints described for $i = 1, ..., 4$ by

$$\begin{aligned}
p(e^i)\tilde{p}_i w_1^i + (1 - p(e^i)\tilde{p}_i)w_0^i - e^i \quad & \geq \quad u(w_E) \\
e^i \in \operatorname{argmax}_e p(e)\tilde{p}_i w_1^i \, + \, \big(1 - p(e)\tilde{p}_i\big] w_0^i \quad & - \quad e.
\end{aligned}$$

Note that the weights in the participation constraint reflect the probabilities conditional on a production task not being completed at the previous stage(s). Moreover, if a worker at the first stage has the appropriate inputs for some production task but fails to complete the task due to lack of effort, the implied cost include the wage cost w_0^i for all successive stages $i > 1$. This is reflected in the value of marginal effort to the firm. For example, for a worker at the first stage, that value is

$$MV_1(de; \{w_1^j, w_0^j\}_j) = p'(e^1)p_1 \left(v_0 - w_1^1 \; - \; (-w_0^1 - w_0^2 - w_0^3 - w_0^4)\right).$$

In general, the marginal effort of worker i to the firm is given by

$$
\begin{aligned}
MV_i(de; \{w_1^j, w_0^j\}_j) &= p'(e^i)p_i \left[v_0 - \sum_{j=1}^{i-1} w_0^j - w_1^i \right] - p'(e^i)p_i \left[- \sum_{j=1}^{4} w_0^i \right] \\
&= p'(e^i)p_i \left[v_0 - (w_1^i - w_0^i) + \sum_{j=i+1}^{4} w_0^j \right] \qquad (7)
\end{aligned}
$$

The marginal benefit to worker i for fixed wage levels is

$$
MB_i(de; w_1^i, w_0^i) = p'(e)\tilde{p}_i w_1^i \; - \; p'(e)\tilde{p}_i w_0^i - 1 = p'(e)\tilde{p}_i \left[w_1^i - w_0^i \right] - 1. \qquad (8)
$$

While the equations (5) and (6) depend on the same exogenous probability p_H, the above equations (7) and (6) depend on the unconditional probability p_i and the conditional probability $\tilde{p}_i$, respectively. The questions whether firms facing input or value uncertainty value effort more, induce higher effort levels, and reward workers more for their effort have different answers depending on which probability is used as a reference point:

Proposition 2

a) Keeping the unconditional exogenous probability fixed that a worker can solve any production task, the equilibrium effort level at firms facing input uncertainty is higher for all workers than at firms facing value uncertainty.

b) Keeping the conditional exogenous probability fixed that a worker can solve a production task, the equilibrium effort level of a worker at the early stages of a firm facing input uncertainty is higher than that of a worker at a firm facing value uncertainty, while the effort of a worker at the latter stages is lower.

The main insight from this proposition is that the drivers determining optimal effort levels differ between firms that face value uncertainty and those that face input uncertainty. For firms facing value uncertainty, the equilibrium effort is determined by the probability of success p_H. For firms facing input uncertainty, the equilibrium effort at early stages is additionally determined by the cost of effort-failure in subsequent stages. The equilibrium effort at latter stages is also determined by the larger marginal benefit of effort to workers due to the increasing conditional exogenous.

3.3 Information Revealed through Output Observation

Finally, I discuss what firms can learn about workers through observing the output.

As before, I assume that workers have a certain type (a, b) with $a \in \{a_1, a_2\}$ and $b \in \{b_1, b_2\}$, but the workers' types are no longer public knowledge: Workers either do not know or cannot credibly signal their type. There are four types of workers. Let π_{ij} denote the prior belief that a worker is of type (a_i, b_j). Observing outcomes, a firm may learn the worker's type. Assume that the workers have a constant wage of $2c$.

First, recall that a firm facing value uncertainty has the following outcome distribution

$$\Pi_V(\{a_i, b_j\}; \theta, \tau) = \begin{cases} v_0 - 2c & \text{with probability } p_H(\tau) \quad \text{if } i = 1, j = 1 \\ 0 & \text{else} \end{cases}$$

Therefore, such a firm updates beliefs as follows

$$\hat{\pi}_{ij}(v_0 - 2c) = \begin{cases} 1 & \text{if } i = 1, j = 1 \\ 0 & \text{else} \end{cases} \quad \text{and} \quad \hat{\pi}_{ij}(-2c) = \begin{cases} \frac{\pi_{11}(1-p_H)}{\pi_{11}(1-p_H)+(1-\pi_{11})} & \text{if } i = 1, j = 1 \\ \frac{\pi_{ij}}{\pi_{11}(1-p_H)+(1-\pi_{11})} & \text{else} \end{cases} \tag{9}$$

In other words, observing a success immediately indicates that a worker's type is (a_1, b_1). However, the firm cannot discriminate between the other three types. Indeed, a sequence of infinitely many failures can converge at any $\hat{\pi} = (0, \hat{\pi}_{12}, \hat{\pi}_{21}, \hat{\pi}_{22})$ with $\hat{\pi}_{12} + \hat{\pi}_{21} + \hat{\pi}_{22} = 1$.

Second, consider a firm that faces input uncertainty. A worker of type (a_i, b_j) working by himself generates the following outcome distribution

$$\Pi(\{a_i, b_j\}; \theta, \tau) = \begin{cases} v_0 - 2c & \text{with probability } p_a p_b & \text{if } i = 1, j = 1 \\ v_0 - 2c & \text{with probability } p_a(1 - p_b) & \text{if } i = 1, j = 2 \\ v_0 - 2c & \text{with probability } (1 - p_a)p_b & \text{if } i = 2, j = 1 \\ v_0 - 2c & \text{with probability } (1 - p_a)(1 - p_b) & \text{if } i = 2, j = 2 \\ 0 & \text{else} \end{cases}$$

Therefore, the firm (and the worker) update beliefs as follows

$$\hat{\pi}_{ij}(v_0 - 2c) = \frac{\pi_{ij} \cdot \text{Prob}(a = a_i, b = b_j)}{\bar{P}} \quad \text{and} \quad \hat{\pi}_{ij}(-2c) = \frac{\pi_{ij} \cdot \big(1 - \text{Prob}(a = a_i, b = b_j)\big)}{(1 - \bar{P})} \tag{10}$$

where

$$\bar{P} = p_a p_b \pi_{11} + p_a(1 - p_b)\pi_{12} + (1 - p_a)p_b\pi_{21} + (1 - p_a)(1 - p_b)\pi_{22}$$

is the probability that a successful outcome $v_0 - 2c$ is observed.

In other words, the beliefs do not converge upon a single successful observation, and if p_a and p_b are distinct the firm (and the worker) can eventually discriminate between all four types.

When the firm facing input uncertainty hires more than one worker, the workers' types interact and the posterior beliefs depend on the firm's organizational design. For example, a firm that optimally organizes in with two workers in one stage, as described by the third entry in table 1 hires two workers of type (a_i, b_j) and (a_k, b_l). If the firm only observes the overall outcome but not which worker contributed the inputs, then the firm can, for example, not distinguish which worker is of which type. In particular, if all outcomes are successful, then nothing is learned about the workers' types except that the two workers complement each other. Also, if the firm optimally organizes in a multistage form and the firm cannot observe the inputs used ex-post, then the firm is not sure about the conditional probability distribution of production tasks workers at latter stages face until posteriors for the workers' types at earlier stages converge.

As with other results before, the main insight from this discussion is how value and input uncertainty differentially affect outcomes and a firm's organizational choices. In this case, the difference is more of degree than qualitatively. For instance, a firm only facing value uncertainty also may have several production tasks that require different inputs and hence may be able to discover more than one type. However, even in this case firms facing value uncertainty know which worker type each tasks helps to discover, and one success in any production task uniquely identifies the worker's type.

4 Discussion

4.1 Multi-stage Organization When Facing Value Uncertainty

The results in the previous section may appear to be driven by different organizational designs rather than by value and input uncertainty, respectively. The more appropriate comparison may be allowing firms facing value uncertainty to organize in multistage sequences. As I show in this section, the difference in organizational form does not account for differential affects observed in section 3.

Assume that the firm can attempt production multiple times, i.e., sample multiple draws of $\epsilon(\theta)$, but the firm stops after one successful outcome. If production was not successful at the first attempt, then the firm continues to a second attempt if and only if

$$p_H V(v_0 - 4c) + (1 - p_H)V(-4c) \geq V(-2c).$$

If it is profitable for the firm to undertake one attempt, then it must be true that

$$p_H V(v_0 - 2c) + (1 - p_H)V(-2c) \geq V(0).$$

Since V is concave, this inequality implies the previous inequality. As a consequence, if it is optimal for the firm to undertake one attempt, it is optimal to undertake infinitely many attempts. In contrast to the case of input uncertainty, the optimal organization for the firm facing value uncertainty does not depend on the probability p_H, beyond p_H being large enough to make production viable at all.

Also note that a multistage organization for a firm facing value uncertainty essential consists of independent stages: The conditional probability of generating a successful outcome in any stage is equal to the unconditional, namely p_H, and is moreover the same at all stages. This implies significant differences between multistage organizations facing value and input uncertainty, respectively.

Significantly, the equilibrium effort levels at a multistage firm facing value uncertainty are less than that at a single stage firm, which proposition 2 showed is lower than that for multistage firms facing input uncertainty, at least at the early stages. The reason for this is as follows: When an outcome is unsuccessful due to effort-failure under value uncertainty, subsequent stages can still complete the task successfully. Such a task yields the same expected profit from subsequent stages as any unsuccessful outcome due to a bad exogenous shock. In contrast, an unsuccessful outcome under input uncertainty cannot be completed in subsequent stages. The expected profit from such a task is the sum of all subsequent failure wages w_0 - it is different from the expected profit for tasks that were not completed successfully due to lack of appropriate inputs.

Because the stages of a multistage organization in a firm facing value uncertainty are identical - in probability of success, in risk compensation, and in optimal effort levels, such an organization cannot be distinguished from multiple attempts made by the same worker. In particular, worker and firm update their beliefs about the worker's type according to the formula (9) used for a single-stage firm.

4.2 State Uncertainty

One interpretation of input uncertainty, which was not considered in section 3 above, is the completeness of contracts. Trivially, firms not facing any input uncertainty always can provide *complete* and *unconditional instructions* with which inputs production should take place. In contract, firms facing input uncertainty can at best provide *conditional instructions* when they implement a multistage organizational form, and no specific instructions when using a single-stage organizational form. In the first case, contracts are naturally complete, in the second case they are inherently incomplete. Despite the contractual incompleteness in the second case, ownership and decision rights do not matter in this setting, because there are no decisions to be made and the workers would not do anything any differently if they had ownership rights. Workers face the same uncertainty about which are the appropriate inputs as the firm.

Nonetheless, the baseline model can be adapted to reflect the impact of "state uncertainty" where contracts are *incomplete due to feasibility constraints*. Consider a setting where the at time $t = 1$, the first input a is chosen as a long-term investment by firm I. At time $t = 2$, the complete state of the world (θ, τ) is learned, and the second input b is chosen as a short-term investment by firm II. Although the optimal choice of b given a and (θ, τ) may be obvious, it may not be practicably possible to describe this optimal choice ex-ante.

This is the world of Grossman and Hart (1986), who describe "a situation in which it is prohibitively difficult to think about and describe unambiguously in advance how all the potentially relevant aspects of the production allocation should be chosen as a function of the many states of the world." In this case, as Grossman and Hart (1986) argue, it is better for firm II to have the ownership rights to the production process and contract with firm I on the provision of the first input than conversely for firm I to be the owner of the production process and ex-ante contract with firm II on the provision of the second input.

This model also aligns with Prendergast (2002), where a worker learns the optimal input at $t = 2$ but the firm has to choose the contract offered to the worker at time $t = 1$. Prendergast (2002) shows that it is optimal for the firm to offer the worker a pay-for-performance contract - essentially making the worker a partial residual claimant. Again, in this case ownership rights matter.

5 Conclusion

One of the large achievements of the twentieth century was for firms to figure out how to reproduce the same product thousands of times. The digital age has made reproduction of many products instantaneously and brought the cost of reproduction close to zero. Products that are not digitally produced have still benefited from the digital revolution through automatized production, digital inventories, and improved supply chain management. Increasingly, growing firms are those that find ways to produce new products frequently. From finding an environmental friendly credit-card replacement for the currently used plastic cards that is compatible with the current infrastructure, over getting soldiers injured in the field better diagnostic and better treatment, to getting more Americans to bike more often - highly valuable tasks abound. All of these tasks, and most significant innovation activity, are characterized by a very high uncertainty about the inputs and expertise that will be needed to solve them.

Yet, we know little about the implications that input uncertainty has on the challenges a firm faces and the organizational choices it must make. This paper contributes toward developing such an understanding. Table 3 summarizes the interaction between value and input uncertainty.

		Value Uncertainty	
		low	high
Input Uncertainty	low	Production	Risky Investment
	high	Innovation	Experimentation

Table 3: Value and input uncertainty can vary independently between high and low. This table shows examples for each of the four possible combinations.

In this paper I have shown that input uncertainty affects the way a firm organizes, how it shares risk with its workers, how it incentivizes them, and how input uncertainty affects the revelation of worker information through the observation of output. Two aspects are particularly important. First, when facing input uncertainty the firm has a larger overall feasible choice set how to organize than when facing value uncertainty. This implies, for example, that outcome variance increases with value uncertainty, but is smallest when input uncertainty is largest. Second, the conditional probability of completing a task is generally different from the unconditional probability. It varies between different stages of an organizational form and becomes equal to one for some organizational forms.

The analysis presented here is but a first step. The challenge moving forward is to better embed input uncertainty into the existing literature on contracts and organizational design, and, more importantly, to establish the distinction between input and value uncertainty empirically.

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