Persuading to Participate: Coordination on a Standard*

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Abstract

We consider firms contemplating to coordinate on a standard in the shadow of a given market mechanism. Firms either coordinate on the standard through a standard-setting organization (SSO) or a market solution—a standard war—emerges. A firm's veto to participate in the SSO triggers the standard war. Participation constraints are demanding and the optimal SSO may involve on-path vetoes. We show that vetoes are effectively deterred if firms can (partially) release private information to a non-complying deviator. We call this instrument informational punishment. Informational punishment relaxes participation constraints and increases the set of implementable SSOs.

1 Introduction

Industries operating in two-sided markets often consolidate to a *de-facto standard*. A standard is a platform that all firms use for their interaction. If the standard is not imposed by a regulator, there are, broadly speaking, two ways how industries set their standard. Either competitors cooperate via a *standard-setting organization* (SSO), or market forces determine the outcome. In the former case, the SSO implements the standard. In the latter case, the standard emerges as the outcome of a standard war.

In this article we model the market solution as a game of incomplete information. An SSO is the alternative to the market. It determines the standard outside the market. An SSO is only implementable if no firm vetoes the SSO. We characterize the subset of *implementable* SSOs taking the set of *available* SSOs as given.

We address two questions. First, *why and when do firms veto the SSO although the SSO involves fewer inefficiencies than the market solution?* Second, *how can strategic information revelation make coordination more likely?*

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The answer to the first question lies in the signaling value of a veto. If a veto decision is informative, firms may veto an SSO to signal private information to their competitors. The answer to the second question is related in that strategic information revelation releases a signal to the competitor too. A firm can use the threat to release information about herself to persuade a competitor to participate in the SSO. We show that the mere option to release such a signal increases the set of implementable SSOs. We use these findings to explain several strategies that firms use when deciding whether to participate in an SSO.

Our contribution is twofold. First, we provide a rationale for strategic information revelation in the context of coordination on an SSO. We show that such revelation can increase the set of implementable SSOs. Second, we show that our insights hold in general. We allow for arbitrary Bayesian games as markets. Similarly, we allow for an arbitrary set of available SSOs subject only to mild minimum requirements. We show that if firms can threaten to reveal information about themselves, some coordination is always optimal. In particular, we show that this threat restores the revelation principle if the set of available SSOs is sufficiently rich.[1]

Coordination on the DVD-standard. To gain intuition, consider the process that led to a standard on high-density data discs (DVD). After a first attempt to coordinate on a standard in 1994 two rivaling technologies were developed: the Multi Media Compact Disc (MMCD) by Sony and Philips and the Super Density Disc (SD) by Toshiba and Time Warner. Although the movie industry was pushing for a unified standard, no cooperation was in sight and a standard war seemed inevitable.

Why did both camps at first refuse to cooperate? One explanation is that they had private information about their prospects in the standard war. In particular, both may have been sufficiently optimistic that their product is likely to prevail in the market. As a consequence, they refused to concede. More strikingly, both parties were optimistic despite holding a common prior.

The reason for mutual optimism is that both parties received a positive signal about their own capabilities in a standard war. Yet, they are less optimistic about their competitor's expected capabilities. Thus, when calculating best responses both put little weight on the event of facing a strong competitor. This mutual optimism implies, in turn, that both expect a favorable outcome of the procedure, something an SSO can at most grant one of them. As a consequence, a strong firm has an incentive to veto an SSO.

In the case of the DVD standard both camps were optimistic. The MMCD camp was convinced that without the patents they held on the compact disc (CD), no successful imple-

[1] If the revelation principle holds, a full-participation mechanism is always optimal. Potential failure of the revelation principle in the standard-setting environment is a direct consequence of the answer to our first question. Without the option to reveal information on-path, vetoes can be optimal irrespective of the set of available SSOs. See also Celik and Peters (2011) for further details.

mentation was possible. The SD camp, however, was convinced that its dual-layer technology was a sufficient advancement that goes far beyond anything based on the CD technology.

According to industry observers a group of technicians from the main computer companies (the so-called technical working group, TWG) played a major role in persuading both camps to form the DVD Consortium (later DVD Forum). In June 1995 Sony executive Norio Ohga shared his view that a standard war was unavoidable. Preparing for the standard war, the TWG announced that they are going to analyze the two proposals. Shortly thereafter both camps announced that they are planning to work together. Indeed, they finally united in the DVD consortium.

Why did the message discipline both camps? The message contained no information on whom the TWG would side with. Instead two other issues are important. First, the announcement was made by a player that had signaled impartiality before. As Toshiba executive Koji Hase puts it, TWG leader Alan Bell '*is fair, he's very fair. He did not side with Toshiba [or] Sony for that matter. He tried to be as fair as possible.*' Second, the announcement implied that the TWG was going to release the outcome of their evaluation at a later date.

To overcome the coordination failure of mutual optimism, the TWG committed to release information about the technologies, if parties could not find a solution on their own. That is, the TWG was not interfering with the market mechanism directly. Instead, it influenced the expected information structure. Moreover, it did so by *announcing* to produce a signal rather than producing the actual signal.[2]

General Results. Our analysis shows that the announcement to produce signals persuades firms to coordinate on an SSO. The announcement relaxes participation constraints and thereby increases the set of implementable SSOs.

In our model, firms contemplating to join an SSO have access to a signaling device. This device allows them to *ex-ante* commit to release parts of their private information in case an opponent firm vetoes the mechanism. If this signaling device is present, an optimal SSO persuades all firms to participate independent of their private information. We call information revelation that aims at deterring a veto of other firms *informational punishment.* Releasing information influences the action choices in the market of all firms—those participating and those vetoing. Consequently, it affects firms' prospects under the market solution.

We show that a firm contemplating to veto the SSO is effectively threatened by informational punishment. Informational punishment decreases firms' outside options which relaxes

[2]Interestingly, the amount of information the TWG could use to produce that signal was controlled by the firms themselves. Prior to its announcement to carry out investigations regarding the quality of the firm's proposed standards, the TWG gathered information about the perceived quality directly from the firms. Firms revealed that private information while asking for advice and trying to convince the TWG that their format is more appealing than that of the competitor.

participation constraints.

On a technical level, informational punishment convexifies the participation constraints. It allows us to formulate a simple expressions for these (relaxed) constraints. Even in complicated environments, the relaxed constraints are easy to handle. Informational punishment is helpful both in environments in which the SSO is chosen from a limited set of options and in environments in which the entire mechanism-design toolbox is available to design an SSO.

Informational punishment has a set of additional attractive features. It separates the signaling effect of a veto from firms' participation decision. That is, informational punishment itself exclusively affects the firms' participation constraints. Yet, it has neither a direct effect on the (expected) outcome of the SSO nor on incentive constraints. The reason is that informational punishment only operates off the equilibrium path.

Our approach is constructive. A designer commits to generate a random public signal about the information she obtains from the participating firms. If firms cannot commit to ignore public information, they update their beliefs once the information is public and rationally expect their opponents to do the same. A firm's continuation strategy is then a best response given these beliefs. In principle the designer can pick any posterior belief as long as the set of posteriors is Bayes' plausible with respect to the prior.

The signal splits the prior information structure. A deviator's expected payoff before receiving the information is the convex combination of the payoffs from the continuation play after each realization.

Informational punishment operates only off the equilibrium path. Yet, it relaxes participation constraints by exploiting non-convexities in a firm's *value of vetoing*, which determines the firm's expected payoff conditional on a veto.

Informational punishment is connected to several real-world phenomena besides communication through a neutral party. Thus, our model directly captures other business strategies common around the standard-setting process. These include announcements about future product developments that could lead to so-called *vaporware* and strategic *leaking of documents*.

These business strategies have different features than communication with an exogenous signaling device. Yet, they implement informational punishment. Beyond these isomorphisms, we address the role of commitment and discuss implications of informational punishment on regulators. Our results are applicable beyond standard setting. They apply to all situations in which coordination takes place in *the shadow* of an inefficient market solution. Examples include crowdsourcing, litigation, strikes and competition with differentiated products.

Related Literature. We adopt Farrell and Saloner (1985)'s view of a market mechanism as a contest between competing standards. Alternatively, firms can coordinate on a standard-setting organization that governs the patent rights.

We follow Farrell and Simcoe (2012) and assume that firms can choose from a set of standard-setting mechanisms to avoid the costly market mechanism. In line with them, we assume that firms hold private information about their own patents. However, different to Farrell and Simcoe (2012), we are not primarily interested in the question whether the *optimal standard* arises. Instead, we are agnostic about the standard's quality, and focus on the *standardization function* (Lerner and Tirole, 2015) of an SSO.

Our own work on conflict management (Balzer and Schneider, 2018) is related in that there, too, we consider an environment in which economic agents can coordinate on a mechanism to circumvent an exogenously given game. In that article we propose a dual formulation of a mechanism-design problem to characterize the second-best arbitration mechanism. However, by assumption and different to the present article, vetoes have no signaling value. Thus, most of the issues discussed here do not arise in Balzer and Schneider (2018). Informational punishment has no effect.

Indeed, in this article we do not focus on the design of a mechanism, but on the design of a *separate signaling device* that supports the implementation of a mechanism. We consider an arbitrary market solution and a (potentially) restricted set of available mechanisms. We show that informational punishment overcomes severe obstacles a designer faces in such an environment when implementing a mechanism. Methodologically, in Balzer and Schneider (2018) the departure from standard incentive constraints causes departure from standard solution approaches. In this article, the departure from standard participation constraints causes the need for informational punishment.

Dequiedt (2007) emphasizes the importance of non-trivial participation constraints in a model about collusion in auctions. Similar to us, he studies how participation constraints restrict the implementable allocations of a mechanism that does not fully control the strategic environment. The crucial difference is that in our model firms *cannot* commit to follow the mechanism's recommendation if the mechanism is vetoed. Instead if some firm vetoes, the mechanism becomes void and firms engage in the market. *All* firms' continuation strategies are best responses to one another given the rules of the market. The mechanism itself influences these responses only indirectly through the information structure it implies *after* firms observed who has vetoed.

Games as outside options have been widely recognized as a driver for the failure to coordinate on a mechanism.[3] The potential for such failure in our model is identical to that identified in Celik and Peters (2011) in a setting of cartel formation. Allowing informational punishment in their setting completely overcomes the participation problem.

We assume that the signaling device is offered by an impartial third-party. That third-

[3]In addition to the aforementioned, also the literature on SSOs as certification entities (Chiao, Lerner, and Tirole, 2007; Farhi, Lerner, and Tirole, 2013) acknowledges this problem.

party can commit to a certain device *before* eliciting firms' information. Thus, concerns of informational opportunism as in Dequiedt and Martimort (2015) do not apply directly. We characterize environments where results are robust to allowing for informational opportunism.

Informational punishment uses the tools of Bayesian persuasion (see the literature following Kamenica and Gentzkow, 2011), in particular convexification (Aumann and Maschler, 1995). Our problem, however, is *not* an information-design problem as information has to be elicited from the firms. That is, the signaling device has to satisfy incentive constraints. Moreover, in the persuasion literature a designer actively persuades firms to pick a certain action. Informational punishment works on a more subtle channel. A signal persuades firms to participate in the proposed mechanism by threatening to release information *otherwise*. Thus, the actual punishment never occurs on the equilibrium path, but the threat alone convexifies outside options. As a consequence, the availability of a communication channel alone increases the set of implementable mechanisms.

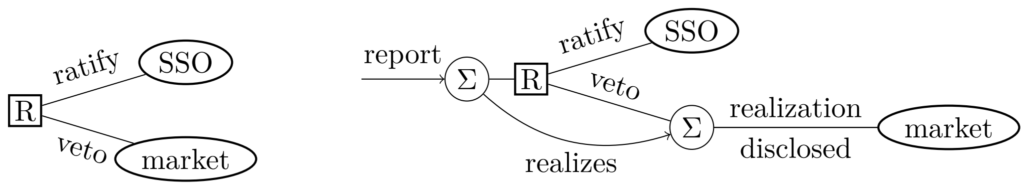
Gerardi and Myerson (2007) and Correia-da-Silva (2017) look at veto-constraint mechanisms too. The main difference is that firms can verify neither a veto nor an acceptance decision. Both articles propose a trembling device to relax participation constraints. The trembling device triggers a spurious veto *on the equilibrium path*. Existence of *on-path* vetoes eliminates the signaling value of an *off-path* veto, as firms cannot credibly signal that they caused the observed veto. In our setup, trembling devices are ineffective since vetoes (or the lack thereof) are publicly verifiable. Instead, the mere promise of informational punishment disciplines firms to participate. Different to trembling, informational punishment has no direct influence on the mechanism itself.

Roadmap. The remainder of this article is structured as follows: In Section 2 we provide a simple model. We first model the standard setting process without informational punishment and determine when coordination on an SSO is possible. We then include informational punishment and show that informational punishment increases the set of parameters in which firms can coordinate on an SSO.

In Section 3 we generalize these insights. We derive minimal conditions on the space of available SSOs such that coordination is always beneficial. In addition, we provide several general properties of optimal informational punishment. We discuss the underlying assumptions of our model in Section 4 and conclude in Section 5. All proofs not provided in the main text are in the appendix.

2 Coordinating on a Standard

In this section we present a model on standard setting that conveys the intuition behind our general result. We focus on a stylized model that highlights the role of informational



(a) without i. p.

(b) with informational punishment.

Figure 1: *(a) Standard setting without informational punishment and (b) including informational punishment.* In the ratification stage (R) firms decide whether to ratify or veto the SSO. If they ratify, the standard is set using the rules of the SSO, otherwise the market determines the outcome. Informational punishment adds a signaling device, Σ, to which firms report *before* (R). The signal realization becomes public only *after* (R).

punishment. We consider two firms with binary types, a specific market and a particularly simple space of available SSOs. None of these restrictions is important for our general results.

Indeed, our general model in Section 3 considers an arbitrary set of firms, types[4], and market mechanisms. The space of available SSOs in the general model is subject to some mild minimal requirements only.

Our main result is that informational punishment helps firms to coordinate on an SSO. Informational punishment itself is a signaling device available to firms. The signaling device commits to release a signal on information provided by the firms. This signal is released with some time lag. Figure 1 sketches the model with and without informational punishment.

We organize this section as follows. We first describe our model setup and state the main result of this section, Proposition 1. We then describe when an SSO is implementable with and without informational punishment. That provides the proof of Proposition 1. Finally, we discuss our result and the main assumptions driving them in the light of real world cases. Formal arguments not in the main text are in the appendix.

Model and Result

The model consists of four parts. A grand game, an SSO, a market, and informational punishment. We describe each separately.

Grand Game. There are two risk-neutral firms looking to establish a standard. Each firm possesses binary private information $c_i \in \{1, k\}$ about its technology. This type is drawn according to a known, firm-specific distribution captured by p_i^0, the ex-ante probability to be type $c_i = 1$.

There are two ways to determine the standard. The market or the SSO. The rules that determine the standard in both ways are known to the parties at the beginning of the game.

[4]Some of our results apply to finite type spaces only, but most hold for continuous type spaces as well. We discuss the reasons in Section 3.

The timing of payoff relevant actions is as follows.

1. The rules of the SSO are announced and firms learn their type realization c_i.
2. Firms simultaneously choose a strategy, that is, a contingent plan of actions that also includes a decision whether to veto the SSO.
3. If no firm vetoed the SSO, the SSO is implemented, otherwise the veto becomes public and firms interact via the market.

The structure of the grand game is commonly known. Only firms' cost functions are private information. Our solution concept is perfect Bayesian Nash equilibrium (Fudenberg and Tirole, 1988).

Market. If the standard is determined via the market, firms non-cooperatively compete for the right to set the standard in a standard war. We assume that winning the standard war provides the winning firm with royalties that have value normalized to 1.

Both firms simultaneously invest in the distribution of their formats. For example, a firm can subsidize upstream third-party developers to use its platform. Alternatively, the firm can foster the distribution of hardware among downstream consumers. Investment increases the chances of winning the standard war. For simplicity we make the extreme assumption that the format of the firm with the highest investment prevails with certainty if that investment is larger than some minimum investment $r > 0$. Ties are broken at random. Suppose both firms invest less than r. Then, the old technology remains the standard and firms receive no royalties. The minimum investment r captures, for example, the necessity to cover the basic needs of upstream or downstream parties to be able to work with the new technology. Investment comes at constant marginal cost c_i. This cost is firm i's private information.

Standard Setting Organization. To bypass the market, firms can coordinate on a standard using an SSO. Coordinating eliminates the cost of the standard war. We take a simplistic approach and assume that the SSO is a simple rule that divides the expected royalties from the standard between the two firms. That is, the SSO can be described via x_1, the *share* of patents firm 1 holds in the newly established standard. Firm 2 then receives the remaining share, $x_2 = 1 - x_1$.

Informational Punishment. Informational punishment consists of a signaling device, Σ_i, for each firm. Each firm reports to her Σ_i *before* she decides whether to participate in the SSO. The signaling device commits to withhold the information until *after* the participation decisions of firms are public. In case of a veto, Σ_i releases a (garbled) version of the information that the firms provided.[5]

Formally, Σ_i is a random variable that maps any report m_i into a distribution over *realizations* σ_i from some arbitrary signal space S_i with at least 2 elements. We are interested

[5]In principle Σ_i can also release a signal after firms have accepted the SSO. That realization is without any effect because firms are already committed to the SSO at that point.

in how Σ_i helps to implement an SSO. Thus, we impose no restrictions on Σ_i and S_i. However, using standard revelation arguments it is without loss to restrict attention to those signaling devices that take only *type reports* as inputs. Further, for our purposes it is sufficient to focus on a binary signal space $S_i = \{l, h\}$ only. Thus, $\Sigma_i : \{1, k\} \to \{l, h\}$. In what follows we refer to l as the low signal and to h as the high signal. We denote the probability that realization σ_i occurs by $\rho_i(\sigma_i)$.

Result. We defer a discussion of the assumptions underlying our model to the end of this section. Instead, we present the main result. It states that informational punishment can help firms to coordinate on an SSO.

Proposition 1. *The set of environments in which firms can coordinate on an SSO strictly increases if informational punishment becomes available.*

Market Solution

We assume without loss $p_1^0 \geq p_2^0$, that is, firm 1's *expected* marginal cost of investment is lower than firm 2's. Let p_i be $-i$'s belief that firm i has marginal cost $c_i = 1$. Firms' strategies and thus their equilibrium payoffs depend on the relation between the two distributions, p_1 and p_2, the cost disadvantage of the high-cost firm k, and the minimum investment r. We say that $I = (p_1, p_2)$ is the commonly-known information structure at the point in time where firms choose their investments.

Given $p_1 \geq p_2$ there are four different kinds of equilibria. Each is unique within a subset of the set of possible information structures, $\mathcal{I}$. Figure 2 illustrates the equilibrium partitioning. Formally it corresponds to

$$
\begin{aligned}
\mathcal{I}_0 &:= \{I \in \mathcal{I} | r > 1 - p_2\}, \\
\mathcal{I}_A &:= \{I \in \mathcal{I} | 1 - p_2 \geq r > (1 - p_2)/k\}, \\
\mathcal{I}_B &:= \{I \in \mathcal{I} | (1 - p_2)/k \geq r > (1 - p_1)/k\}, \\
\mathcal{I}_C &:= \{I \in \mathcal{I} | (1 - p_1)/k \geq r\}.
\end{aligned}
$$

We now characterize the market outcomes for an arbitrary information structure I.

Lemma 1. *Consider the game described above and take any two probability distributions*

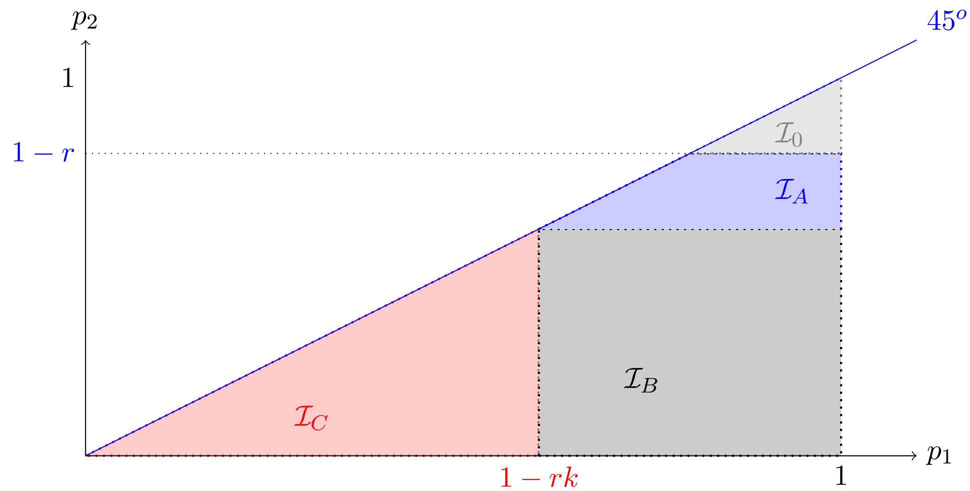


Figure 2: Partitioning the information set, given $p_1 \geq p_2$. Each partition corresponds to a type of equilibrium. See Lemma 1 for an analytical description.

$I = (p_1, p_2)$ with $p_1 \geq p_2$. Then, the expected equilibrium payoffs $V_i(c_i)$ are

$$V_i(1) = \begin{cases} 0 & \text{if } I \in \mathcal{I}_0 \\ 1 - r - p_2 & \text{if } I \in \mathcal{I}_A \\ (1-p_2)\frac{k-1}{k} & \text{if } I \in \mathcal{I}_B \cup \mathcal{I}_C \end{cases}$$

$$V_1(k) = \begin{cases} 0 & \text{if } I \in \mathcal{I}_0 \cup \mathcal{I}_A \\ (1 - kr - p_2)\frac{k-1}{k} & \text{if } I \in \mathcal{I}_B \\ (p_1 - p_2)\frac{k-1}{k} & \text{if } I \in \mathcal{I}_C \end{cases}$$

$$V_2(k) = 0.$$

The intuition follows from the familiar logic of contest games (see e.g. Siegel, 2014, for further details). The weakest type of the (ex-ante) weakest firm receives zero expected payoff from participating. In addition, low-cost types of both players obtain the same utility. This follows because the rules of the game inevitably lead to a common upper bound on the low-cost types' equilibrium investment supports. The remaining intuition is captured in Figure 2. Region $\mathcal{I}_0$ corresponds to a situation in which the likelihood of meeting a high-cost firm 2 is very small. Thus, a low-cost firm 1 has no incentive to gamble on such an event and therefore invests to beat her low-cost opponent. This behavior leads to full rent dissipation.

If the likelihood of meeting a high-cost firm 2 is intermediate (region $\mathcal{I}_A$), a low-cost firm 1 has an incentive to gamble on meeting a high-cost firm 2. This gamble results in a reduction of the low-cost firm 2's investment. The reduction leads to positive rents for both low-cost firms. If the likelihood of meeting a high-cost firm 2 is relatively large (region $\mathcal{I}_B$ and $\mathcal{I}_C$), high-cost firms enter the contest too. Their investment behavior depends on the likelihood of a high-cost firm 1. If this likelihood is small ($\mathcal{I}_B$), a high-cost firm 2 is still reluctant to invest as she most likely meets a low-cost firm 1. In turn, the high-cost firm 1 enjoys large payoffs. If, however, the likelihood of a high-cost firm 1 is similar to that of firm 2 (region $\mathcal{I}_C$), both high-cost firms compete frequently reducing the payoff of a high-cost firm 1. Low-cost firms expected payoffs in $\mathcal{I}_B$ and $\mathcal{I}_C$ are a function of firm 2's type distribution only.

Coordinating on a Standard-Setting Organization

In this step, we derive conditions on the environment such that a perfect Bayesian equilibrium exists in which all types of all players accept the SSO. If such an SSO exists it is accepted with probability 1 in equilibrium. Rejections happen only off the equilibrium path.

In principle, off-path beliefs are arbitrary. However, we can only choose the belief the non-deviating firm holds about the deviator when observing a veto. The deviator's own belief about the non-deviating firm has to coincide with the prior. She cannot learn anything from her own veto decision. To facilitate coordination, we assume that the non-deviating firm $-i$'s (off-path) belief is degenerate and $p_i = 1$ upon observing a veto by her opponent i. From the point of view of i this is the worst off-path belief $-i$ can attach to its deviation.

If under these off-path beliefs firms cannot coordinate on any SSO, then no SSO exists under any beliefs.[6] The potential information structures after a veto are thus $I_1 = (1, p_2^0)$ and $I_2 = (p_1^0, 1)$. Information structure I_1 is that after a veto of firm 1, I_2 is that after a veto of firm 2.

The off-path information structure determines the value of vetoing, $v_i(1) = V_1(1|I = I_i)$, for the deviator. Since $p_1^0 \geq p_2^0$, by Lemma 1 firm 1's value of vetoing is its expected payoff from the market solution under the prior, that is, $V_1(1|(1, p_2^0)) = V_1(1|(p_1^0, p_2^0))$. Firm 2's value of vetoing can be obtained by swapping indexes in Lemma 1 and using the prior p_1^0 for p_1. High-cost types have always lower values of vetoing than low-cost types.

Coordination on an SSO is possible if and only if $v_1(1) + v_2(1) \leq 1$. In the graph of Figure 3 this condition fails for any $p_2 < p''$. If both parties are sufficiently optimistic, then a standard war seems unavoidable. Note that optimism in this model is directly related to the perception of the opponent's cost function. A low-cost firm is optimistic about the standard war if and only if it is sufficiently confident that the opponent has high cost.

Numerically, the following parameter values induce such situation.

Example 1. Let $k = 5$, $p_1^0 = 1/3$ and $r = 1/6$.

Lemma 2. *Consider Example 1. Without informational punishment an implementable SSO exists if and only if* $p_2^0 \geq 1/3$.

[6] In principle we can pick any off-path beliefs for the non-deviating firm for our qualitative argument. For an interpretation of different off-path beliefs in a similar model see Zheng (2017).

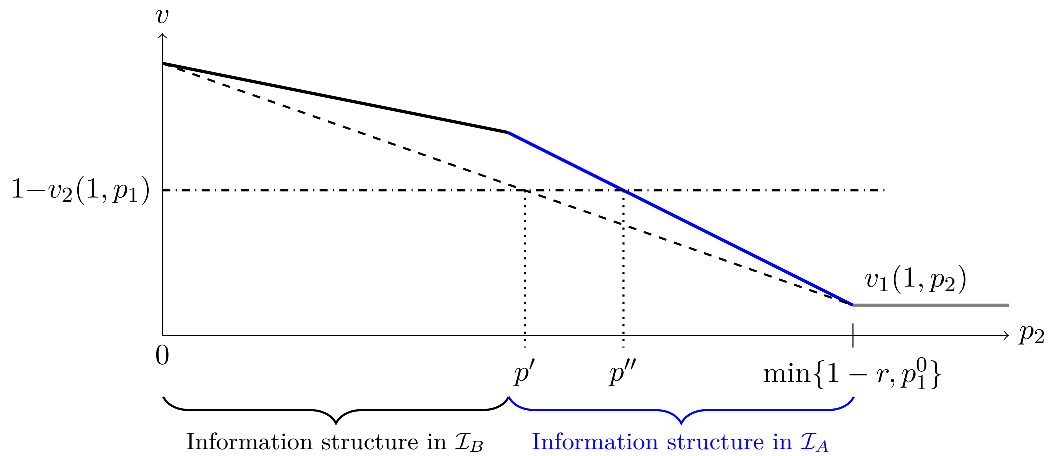


Figure 3: The value of vetoing for firm 1 given firm 2 assigns a probability p_1 to firm 1 having cost 1. The dashed line denotes the function's convex closure. The dot-dashed depicts the residual resources after paying the minimum share to firm 2. For $k = 5$, $p_1 = 1/3$ and $r = 1/6$, it follows that $p' = 7/24$ and $p'' = 1/3$.

Proof. By Lemma 1 the value of vetoing is (weakly) monotone in p_{-i}. The value of vetoing for firm 2 is $v_2(p_1^0, 1) = 1 - p_1^0 - r = 1/2$. Monotonicity implies that if an SSO is implementable for $p_2^0 = \hat{p}$, it is implementable for $p_2^0 > \hat{p}$. Conversely, if it is not implementable for $p_2^0 = \hat{p}$ it is not implementable for $p_2^0 < \hat{p}$. We guess that the cutoff belief, $\hat{p}$, is in $\mathcal{I}_A$. Then the value of vetoing for firm 1 is $v_1(1, p_2^0) = 1 - p_2^0 - r$. That expression is weakly below 1/2 iff $p_2^0 \leq 1/3$. Thus, the cutoff is indeed in $\mathcal{I}_A$. □

Using Informational Punishment

We now allow the mechanism to use informational punishment. Without further loss we use the convention that the low signal shifts the prior towards the low-cost type, and the high signal shifts the prior towards the high-cost type. We characterize situations in which firms expect to coordinate on an SSO. Throughout our discussion we assume firm 1 has deviated by vetoing the SSO.

The Market after the Signal Realization. We guess players report truthfully to Σ_i on the equilibrium path and verify our guess later. A veto by firm 1 leads to an off-path belief $p_1 = 1$. Thus, the the signal realization *about* firm 1, σ_1, provides no additional information.

Suppose the signal about firm 2, Σ_2 has realized to σ_2. It carries information about firm 2 (the non-deviator). Firm 1 (the deviator) uses that information to form a posterior belief $p_2(\sigma_2)$. The information structure is $I = (1, p_2(\sigma_2))$. The continuation payoffs follow from Lemma 1.

Consistent Signals. We now turn to the properties of the signal. Whatever signal realizes, firm 1 forms a posterior. Posteriors are consistent with the prior. Consistency is a direct consequence of the firm's updating process. Firm 1 uses its knowledge about the mapping Σ_2, the prior, and the realization σ_2 and updates the belief about its competitor to a posterior p_2 via Bayes' rule.

Consistency with the prior implies[7]

$$\rho_2(\sigma_2 = l)p_2(\sigma_2 = l) + \rho_2(\sigma_2 = h)p_2(\sigma_2 = h) = p_2^0. \tag{1}$$

The ex-ante likelihood that $\sigma_2 = l$ realizes is

$$\rho_2(\sigma_2 = l) = p_2^0\rho_2(\sigma_2|c_i = 1) + (1 - p_2^0)\rho_2(\sigma_2|c_i = k). \tag{2}$$

The Value of Vetoing. Knowing the properties of the signal and the expected payoffs conditional on the realization leads to a *value of vetoing* for a deviating low-cost firm of $v_1(1;\Sigma) := \rho_2(\sigma_2{=}l)V_1(1|I{=}(1,p_2(l))) + \rho_2(\sigma_2{=}h)V_1(1|I{=}(1,p_1(h)))$. The value of vetoing is firm 1's expected payoff at the point were it decides to veto the SSO. At this point the firm is unaware about the signal realizations.

To find the optimal signal we minimize $v_1(1;\Sigma)$ subject to consistency. This isolation provides a fully revealing high signal, $p_2(h) = 0$. The low signal, in turn, is not fully revealing and induces $p_2(l) = 1 - r$. Equation (1) determines the likelihood $\rho_2(\sigma_2 = l) = p_2^0/(1 - r)$.

Graphically, we obtain the optimal signal structure directly from Figure 3. Three observations lead to the result. (i) Any posterior $p_2(\sigma_2)$ corresponds to a posterior value of vetoing which is on the graph of $v_1(1;p_2(\sigma_2))$, (ii) any signal structure is a mean preserving spread around the prior, p_2^0, and (iii) the signal structure implies an expected value of vetoing that is the convex combination of the two posterior values, $v_1(1;p_2(\sigma_2))$, with $\rho_2(l)$ as the weight. Combining these three observations immediately leads to the result. Geometrically, $v_1(1;\Sigma)$ has to be on the line connecting the two post-realization payoffs $v_1(1;p_1(l))$ and $v_2(1;p_1(h))$. Moreover, $v_1(1;\Sigma)$ is the value of that line evaluated at the prior p_2^0. The dashed line in Figure 3 draws that line for the optimal signal.

Why is that signal optimal? The graphical analysis delivers the intuition. We want to minimize $v_1(1;\Sigma)$ over Σ. A straight line between two points on a concave graph is below the graph. Thus, to find the smallest value of vetoing we have to look for the largest convex function weakly below $v_1(1;p_2)$. The dotted line in Figure 3 provides that function for information structures $\mathcal{I}_A$ and $\mathcal{I}_B$. The optimal function picks the two extreme points in that region. One is $p_2 = 0$ and the other is $p_2 = \min\{1-r, p_1\}$. Note that $p_2 = 1-r$ because the veto belief $p_1 = 1$.

[7]The Bayesian persuasion literature refers to consistency as *Bayes' plausibility.*

Finally, we have to verify that truthfully reporting to the signaling device is incentive compatible. Each firm that plans to cooperate considers the information it provides to the signaling device as irrelevant on the equilibrium path. In fact, firms use the signaling device to threaten their opponent with informational punishment rather than planning to carry out that punishment. Thus, truthful reporting is optimal. Consider a firm that plans to veto the mechanism. It has an incentive to strategically report to the signaling device if the realization influences the other firm's action in the market solution. Yet, once a veto becomes public, the other firm becomes aware of a deviation and may (as part of its off-path belief) disregard any realized signal. Thus, the optimal signal is incentive compatible.[8]

We now prove our initial statement, Proposition 1, using Example 1.

Lemma 3. *Consider again Example 1. If informational punishment is available, firms can coordinate on an SSO if and only if* $p_2 \geq 7/24$. *The optimal SSO is* $x_1 = 4/5 - (24/25)p_2^0$, *and the optimal signal either reveals that the non-deviator has high cost with probability 1 or that she has low cost with probability* $5/6$.

Proof. If $p_2^0 \geq 1/3$, Lemma 2 applies. For all other cases plug the posteriors constructed above into the expressions of Lemma 1. Then, $V_i(1|I = (1,0)) = 4/5, V_i(1|I = (1, 1-r)) = 0$. In addition, $\rho_i(\sigma_i = l) = 6p_i^0/5$. Taking expectations yields $v_i(1;\Sigma) = 4/5 - (24/25)p_{-i}$. Coordination on an SSO is possible if $\sum_i V_i(1;\Sigma) \leq 1 \Leftrightarrow p_2 \geq 7/24$. □

Interpretation and Discussion

Informational punishment is a simple yet powerful signaling device. We require (only) the following features. The device can commit to (i) conceal information for some time, and to (ii) release that information in a garbled way after the concealment time has passed.

Informational punishment is theoretically appealing. It is easy to model, highly tractable, and separated from the structure of the SSO. These features make informational punishment a useful modeling tool in environments in which mechanisms aim to bypass an existing market. We confirm these insights in a general setting in Section 3. In the remainder of this section, we discuss the implications and interpretations of our above findings.

Regulation. Informational punishment increases the potential to overcome inefficiencies without direct regulation. Instead, the mere presence of a signaling device facilitates cooperation. The flip side of this argument is that in cases in which competition is inefficient for the firms but beneficial for society, it becomes harder to sustain competition if such a signaling device exists.

[8] In the discussion below we consider an extension to the model in which the signal is able to produce some "hard" evidence on its own, but the result (and the general logic) remain.

In standard setting both scenarios are plausible. A standard war may be harmful to consumers because of the uncertainty it induces. For example, downstream firms might be less likely to invest in developing complementary technology because of that uncertainty. Moreover, consumers may end up with the wrong playback devices and would need to purchase an additional device, once the standard is established.[9] At the same time, however, a standard war may drive down prices for these playback devices so much that buying two devices is cheaper than buying only one absent competition.

Consider a market which is in the process of developing a standard. Our results have the following implications on regulation. Fostering the availability of signaling devices is beneficial if cooperation is socially desirable. In contrast, prohibiting such devices is beneficial if competition is socially desirable. In the latter case it is important for regulators to recognize that the availability of a device itself may be sufficient to ensure cooperation. That is, although no evidence for communication has realized, firms may have used the threat of such communication to coordinate. Finding evidence ex-post may be harder than banning that option ex-ante. Banning informational punishment ex-ante involves—as we will see in the following—regulating or banning vaporware, enforcing strict laws against whistle blowing in industry contexts, and regulating firms' communication with the press and on social media.

Other Forms of Informational Punishment. Above we model the signaling function in a very specific way. It relies exclusively on soft information, can fully commit to a revelation strategy, and is offered by a non-strategic third party. Specifically, we assume that informational punishment is a signaling device that processes soft information in a given way. That is, informational punishment can neither verify nor disprove the information that firms provide. While such a device seems to be the tool at hand in the DVD case, there are different alternative ways to produce these signals. Some of these employ a more sophisticated technology than simple information garbling. However, neither of these assumptions is crucial. Indeed, several other forms of signaling devices provide the same result.

Vaporware. The existence of vaporware is a frequently observed business strategy (Shapiro and Varian, 1998). A firm announces a product that is not yet fully developed. The likelihood of the product's realization is correlated with the underlying cost function. Once time comes, the market observes whether the developments have realized as claimed or whether the firm failed to do so and the product was simply vaporware.

In the product announcement stage the firm can control what type of product it announces. The announcement itself is "cheap" in the sense that the firm is free to announce products which are never rolled out. Depending on the chosen announcement, however, the signal of the outcome (roll out/vaporware) may be judged differently.

[9] In addition, consumers might delay their purchasing decision to the future, because of the uncertainty. By doing so, they forgo utility from consumption.

In the case of vaporware the mechanics of the signaling device are different from the one described above. Instead of privately reporting their (soft) information to an existing signaling device, the privately-informed firms publicly choose the signaling device itself. The play of this signaling-device-selection game leads to some signaling device. Its realization, in turn, directly depends on the true state of the world. That is, it depends on the firm's private information, rather than on the firm's soft information.

Yet, the model is isomorphic to our setting. To see this, start with the model from above, but assume firms choose their product announcements to implement the optimal signal. That is, both the high-cost firm and the low-cost firm announce a product that is sufficiently easy to launch for a low-cost firm. If the firm does not manage to launch the product, its high cost is revealed. Ability to launch the product, on the other hand, is not conclusive for low cost.

The only difference to our model is that a deviator is now in principle able to prove its type. For a low-cost deviator such proof is irrelevant as the non-deviating firm holds that belief already. A high-cost deviator, however, never profits from proving its high cost. Finally, all non-fully revealing signals are considered in light of the off-path belief $p_i = 1$. Thus, these signals confirm that belief. Results are identical.

Leaking Documents. Our second alternative interpretation is closer to the original model, yet the real-world procedure differs substantially. Suppose firms have the ability to leak some documents to an independent journalist. If the documents are sufficiently informative the journalist is going to investigate the story and eventually publishes it.

How the news is interpreted by the industry depends not only on the information the firm leaked to the journalist, but also on the journalist's approach to gather information from independent sources. Naturally, this process involves some randomness. Thus, such a journalist serves as a signaling device, while the documents leaked are the message.

Verifiable Information. An intermediate case between informational punishment in our model and the vaporware implementation is that firms provide a neutral expert with information, but that expert has the option to (partially) verify these claims. In that case, firms provide soft information to a neutral third party who investigates these claims. It either finds supporting or dissenting evidence to the claims and reports that evidence accordingly. Depending on the quality or the effort level of the third party, these investigations are more or less informative. Again, under this signaling device results are identical to those in our baseline model. In the case of verifiable information, all firms claim low cost to the third party. The third party then either finds dissenting evidence (the h-signal) or cannot disprove the claims (the l-signal). All other aspects are identical but for the fact that a deviating firm has the ability to prove its high cost. As in the vaporware context, it has no incentive to do so.

Non-Committed Third-Parties. Suppose the third party that provides the signal is itself a strategic player in the grand game. It may be hard for her to commit to a signal *before* obtaining parties' information. The TWG's main goal in the DVD example was to prevent another standard war and to force Toshiba and Sony into cooperation. Thus, the TWG may have had an incentive to choose Σ not before but after talking to the two parties. As described in Dequiedt and Martimort (2015) such informational opportunism can have severe consequences on outcomes.

The optimal signaling device, Σ^{EPIC}, allowing for such informational opportunism, however, is identical to the optimal signaling device under ex-ante commitment, Σ. To construct Σ^{EPIC} it is useful to identify the designer by the message she received. We call it the designer's type. We say a *high* (*low*) device knows the non-deviating firm has high (low) cost. Each type can now decide upon a mapping from her information to a set of realizations. That mapping becomes public together with the realization.

We construct a pooling equilibrium in which each type announces the same Σ^{EPIC}=Σ and reports her private information truthfully to that mapping.

Consider first the *low* type. She is indifferent between any mapping that does not increase the value of vetoing for a type-1 cost deviator. That is, any mapping from a high-cost to signal outcomes such that $p_2(\sigma^{epic} = l) \geq \min\{1 - r, p_1^0\}$ is incentive compatible. Indeed, by announcing Σ^{EPIC} she makes sure that the low signal realizes with probability 1.

Next consider the *high* type. She wants to pool with the *low* type in the most credible way. Indeed, if she deviates from announcing Σ^{EPIC} the firm that vetoed holds off-path belief on her being the *high* type. Thus, Σ^{EPIC} satisfies her incentive constraints.

Allowing for informational opportunism does not alter our results. In the general model in Section 3 the considerations explained here do not generalize to any environment. Instead we discuss a broader version of the informational opportunism at the end of Section 3.

Failure to Coordinate Despite Informational Punishment. Our model shows that informational punishment can help to discipline parties to coordinate on a standard in certain environments. Yet, for any $p_2 < p'$ in Figure 3, no SSO of the kind "x_1" exists even with informational punishment. Our model predicts a standard war in these cases without further negotiations.

In reality we seldom observe such outcomes. Even if a standard war occurs eventually, we typically observe severe negotiations before hand. For example, before the standard war between HD DVD and Blue-ray broke out, several rounds of negotiation had taken place. The reason our model does not predict such negotiation lies in our stylized view of SSOs. While in reality, there are many ways how firms can coordinate on a standard we (artificially) restricted ourselves to a single take-it-or-leave-it offers.

We analyzed these limited mechanisms for several reasons. First, they are simple. Second, they allow us to focus on the mechanics of informational punishment. Third, if the SSO satisfies the participation constraints of all types of firms, the allocation is on the Pareto frontier.[10]

The main drawback of the fixed splitting rule is that even when we allow for informational punishment, we cannot guarantee that an acceptable SSO always exists. One questions immediately arises from this observation: How do the benefits of informational punishment generalize to richer mechanism spaces? The answer to this question is provided in Section 3. We show in Section 3 that informational punishment (i) guarantees participation in an SSO, and (ii) increases the set of implementable SSOs if the space of SSOs satisfies mild minimal restrictions.

Underlying Model Assumptions. The simplifying technical assumptions we made in this section are only for the ease of exposition. In Section 3 we drop most of these assumptions. We thus restrict discussion here to the underlying economics.

We assume that vetoes become public. This only requires that a firm *can* verify its veto. Indeed, vetoes have a signaling aspect. Often, a veto signals confidence in winning the standard war and may thus provoke less aggressive actions by a rational competitor. In the DVD case, absence at the SSO meetings would credible signaled a firm's veto decision.

We model the standard war as a contest with some minimum investment. In a standard war both firms invest in the distribution of their standard and investment increases the chances of winning the war. The minimum investment is required if the old standard replaces (in part) some previously existing formats. In the DVD case these formats were mainly CD and VHS at that time. Earlier attempts to replace CD and VHS formats, e.g. by the LaserDisc or the MiniDisc, failed because the firms did not manage to invest the sufficient amount generating the critical market penetration.[11]

In our model, informational punishment requires a trustworthy information gatekeeper. In particular, at the ratification stage the signal structure is public but not the signal realization. We have seen that this assumption is innocuous in many aspects in our stylized model. Yet, in the DVD standard process the TWG acted as trustworthy information gatekeeper. Indeed, the TWG had published a list of nine vague "objectives" for a high-density disc. From the observer's point of view these objectives did not produce a signal directly. However, it seems likely that the two camps themselves may have had a good idea about the TWG's evaluation *procedure* and the implied uncertainty.

As a benchmark we assume that once firms agree to the SSO, they are committed to its rules. In Section 3 we weaken this assumption and show that all our results continue to hold.

[10] Analyzing richer classes of available SSOs increases the complexity of the solution approach. In Balzer and Schneider (2018) we address the obstacles along the way. Here we focus on the role of informational punishment.

[11] See the textbook of Shapiro and Varian (1998) for more information and case studies on strategies in standard wars.

3 General Model

In this section we generalize the model from Example 1. We allow for an arbitrary (finite) number of firms and an arbitrary (one-dimensional) type space. In addition, we allow for any market game. Moreover, the set of available SSOs is arbitrary too, but it can at least replicate the market outcome.

We show that under these general conditions full participation is optimal, and signals only realize off the equilibrium path. Moreover, for the special case of finite type spaces informational punishment convexifies the participation constraint.

We model the market as an arbitrary exogenously given game of incomplete information. An SSO is an alternative game of incomplete information. As in Section 2 the SSO is accepted if and only if all firms decide to join. Finally, we model informational punishment exactly as in Section 2. It is a simple signaling device to which all firms can send information. That device releases its signal based on firms' reports after firms made their participation decision. Notationally it is convenient to follow the mechanism-design literature by describing games as decision rules that map actions (i.e. type reports) into outcomes.

Setup

Firms and Information Structure. There are N firms, indexed by $i \in \mathcal{N} := \{1, ..., N\}$. Each firm has a private type $\theta_i \in \Theta_i$ and $\Theta_i \subset \mathbb{R}$ is compact. The state $\theta := \theta_1 \times ... \times \theta_N \in \Theta$ is initially distributed according to a commonly-known distribution function $I^0(\theta)$, the *prior information structure*. Let $\theta_{-i} := \theta \setminus \theta_i$, and define the marginal $I_i^0(\theta_i) := \int_{\Theta_{-i}} I(\theta_i, d\theta_{-i})$ with support $supp(I_i^0) \subseteq \Theta \setminus \theta_i$. This formulation covers both finite and convex type spaces.[12]

Throughout the article an information structure I is a commonly-known joint distribution over the state θ. The only restriction we impose on I is that it is absolutely continuous w.r.t. I^0, that is, $supp(I) \subseteq supp(I^0)$. Given its type, θ_i, a firm's *belief* about the other firms' types is the conditional distribution $I(\theta_{-i}|\theta_i) = \frac{I(\theta_i, \theta_{-i})}{I_i(\theta_i)}$, where $I_i(\theta_i)$ is the marginal of I. Following Bergemann and Morris (2016) the set $\mathcal{I}^0$ consists of all information structures for which I^0 is an expansion. That is, $I \in \mathcal{I}^0$ if and only if there exists a random variable $\widetilde{\Sigma}$ which maps types into distributions of signals such that the realization σ together with $\widetilde{\Sigma}$ and I^0 implies I via Bayes' rule.

Basic Outcomes, Decision Rules, and Payoffs. There is an exogenously given set of basic outcomes, $Z \subset \mathbb{R}^K$, with $K < \infty$. Firm i values the basic outcome $z \in Z$ according to

[12] As we will see, most of our results do not rely on finding the *optimal* signal. Thus, measurability issues such as those discussed in the online appendix of Kamenica and Gentzkow (2011) do not occur. The only result to which these concerns potentially apply is Proposition 4. For simplicity and to maintain the intuition from the binary example in Section 2, we state Proposition 4 assuming a finite type space. However, following Kamenica and Gentzkow (2011) a similar result can be obtained for a continuous type space.

a Bernoulli utility function, u_i, defined over Z.

We represent the rules of a game by a decision rule, $\pi : \Theta \to \Delta(Z)$. This rule is a mapping from type *reports* to probability measures over outcomes, $\mu_\pi(\cdot|\theta) = \pi(\theta)$.

Market Solution. The market solution is an exogenously given game of incomplete information. We assume that an equilibrium exists for any information structure $I \in \mathcal{I}^0$ and take the equilibrium-selection rule as given. Fix an information structure I. The market solution induces a decision rule π_I^M. Under this decision rule the expected utility of a truthfully reporting firm i with type θ_i is

$$\begin{aligned} v_i(\theta_i, I, \pi_I^M) &:= \int_{\Theta_{-i}} \int_Z u_i(z, \theta_i, \theta_{-i}) d\mu_{\pi_I^M}(z|\theta_i, \theta_{-i}) I^0(d\theta_{-i}|\theta_i) \\ &= \max_{m_i \in \Theta_i} \int_{\Theta_{-i}} \int_Z u_i(z, \theta_i, \theta_{-i}) d\mu_{\pi_I^M}(z|m_i, \theta_{-i}) I(d\theta_{-i}|\theta_i), \end{aligned}$$

almost everywhere conditional on I, that is, $\forall \theta_i \in supp(I_i)$. The second line follows because π_I^M is incentive compatible with respect to the information structure I (I-IC henceforth). That is, truthful reporting is optimal for all types of all firms given π_I^M.

Fix $\mathcal{I}^0$. Existence of equilibrium implies that we can represent the collection of possible market outcomes by $\Pi^M := \{\pi_I^M\}_{I \in \mathcal{I}^0}$. Element π_I^M is I-IC. Other than assuming existence of equilibrium under $\mathcal{I}^0$ we impose no further restrictions on Π^M.

Standard-Setting Organization. The standard-setting organization (SSO) is an exogenous alternative to the market solution. Any SSO is a game of incomplete information. We represent the set of available SSOs by a collection of decision rules Π. Given π and an information structure I, we define each firm's optimal reporting strategy $m_{i,I}(\theta_i)$. We collect all firms' reports in $m_I(\theta)$. Playing an equilibrium of π implements the decision rule $\pi_I := \pi \circ m_I : \Theta \to \Delta(Z)$ which is I-IC.[13]

The set of available SSOs, the collection Π, may be restricted. Restrictions may come from legal or institutional constraints, or the infeasibility of certain outcomes. We assume the following two minimal requirements on the set of available SSOs:

(i) $\Pi^M \subseteq \Pi$, and

(ii) Π is closed under convex combinations, that is, if $\pi, \pi' \in \Pi$, then for any $\lambda : \Theta \to [0, 1]$ $\lambda\pi + (1 - \lambda)\pi' =: \pi^\lambda \in \Pi$.

The first property implies that the SSO can reenact the market. The second property implies that if two games (1 and 2) are part of the available SSOs, so is the game in which

[13] Although any decision rule in Π represents a direct-revelation mechanisms, truthful implementation may not be guaranteed. Indeed, Π is a shorthand for all possible game forms and m_i is a firm's action. The equilibrium play of each $\pi \in \Pi$, together with the prior information structure I, induces some I-IC decision rule.

game 1 is played for certain type profiles and game 2 for the remaining type profiles.

Apart from these minimal requirements we impose no further restrictions on Π. Thus, we do not restrict attention to mechanism-design problems in the classical sense. Instead we assume an exogenously given set of particular games, provided that replicating the market is part of this set. This assumption includes also the option of pure 'mediation' within the market.

Informational Punishment. Finally, we assume that a signaling device Σ is available to all firms. The N-dimensional random variable $\Sigma : \Theta \to S$ maps type reports into realizations in some signal space $S \equiv S_1 \times S_2 \times .. \times S_N$ with $|S_i| \geq |\Theta_i|$. We denote the realization of Σ by $\sigma \in S$ and that of a particular Σ_i by $\sigma_i \in S_i$.

Timing. At the beginning, firms learn their types and observe π. Then, they simultaneously send a message m_i^{Σ} to Σ. Next, firms simultaneously decide whether to veto the SSO. If at least one firm vetoes the SSO, the set V of vetoing firms becomes common knowledge and the signal realizations σ become public. Firms use that information to update to an information structure $I^{V,\sigma} \in \mathcal{I}^0$ and $\pi^M_{I^{V,\sigma}}$ is implemented via the market. If firms collectively ratify the SSO, they send a type report m_i to the SSO. The SSO implements π.

Solution Concept and Veto Beliefs. We characterize those SSOs that are implementable as a perfect Bayesian equilibrium (PBE) of the grand game in the sense of Fudenberg and Tirole (1988).

PBE restricts off-path beliefs through the 'no-signaling-what-you-don't-know'-condition. In particular, it implies that no firm i can learn about the types of other firms from her own participation decision, both on the equilibrium path and off the equilibrium path. We make frequent use of *veto information structures*, I^V. A veto information structure is the information structure that arises *after* an observed veto, but *before* the realization σ. PBE implies that $I^V(\theta_{-i}|\theta_i) = I^{V\setminus i}(\theta_{-i}|\theta_i)$ for any $i \in V$ and $I^V(\theta_{-i}|\theta_i) = I^{V \cup i}(\theta_{-i}|\theta_i)$ for any $i \notin V$. In addition, all but first-node off path beliefs on deviators are derived via Bayes' rule. The remaining—off-path—beliefs are arbitrary.[14]

The Signaling Value of a Rejection

In this part we provide the intuition behind the failure of the revelation principle *absent* informational punishment. We show that even if the set of available SSOs is arbitrarily large, the set of I^0-IC decision rules may not coincide with those implementable by the SSO. Instead, some distribution of outcomes can only be implemented if some types veto π with positive probability on the equilibrium path. A detailed discussion of this phenomenon alongside a specific example is in Celik and Peters (2011).

[14] In our setting a player is at most observed to deviate once. More complicated off-path belief cascades are not possible in our model.

Absent informational punishment the revelation principle for setting up SSOs fails. The reason is that outside options are endogenously determined by a strategic game, the market solution.[15] To understand that failure assume that informational punishment is not available. We consider a firm i that contemplates to deviate by vetoing the SSO.

Suppose the designer proposes an SSO, π, that all firms are expected to accept. Then, on the equilibrium path the SSO implements π_{I^0}. A veto by i triggers a known information structure I^i. The resulting market solution is $\pi^M_{I^i}$. Firm i participates only if it prefers the expected outcome, π_{I^0}, to the potential outcome resulting from vetoing, $\pi^M_{I^i}$.

The only degree of freedom in I^i is the veto belief on firm i, $I^i(\theta_i)$. All other elements are pinned down by the no-signaling-what-you-don't-know condition of PBE. When contemplating to veto, firm i expects all firms to participate irrespective of their type. Thus, after firm i vetoed, the belief of i, $I^0(\theta_{-i}|\theta_i)$, coincides with the prior. In contrast, any firm j holds the same arbitrary but known off-path belief $I^i(\theta_i)$ about firm i and the prior belief about any non-deviating firm. Combining these beliefs yields the information structure I^i.

Suppose now that some types of firm j reject the SSO in equilibrium. Then, firm i cannot secure herself $\pi^M_{I^i}$. Instead the information structure after firm i's veto depends on the observed acceptance decisions of the other firms. Thus, when contemplating to veto, firm i faces a lottery over potential information structures. By Jensen's inequality, if her expected utility v_i is concave in I, then the expected payoff from the lottery over the information structures is below the payoff from the expected information structure.

Concavity of v_i means that a firm's value of information in the market is negative. In this case, on-path vetoes of some j relax i's participation constraint. Full participation may not be optimal. If informational punishment is available, however, such concerns become obsolete.

Informational Punishment

If informational punishment is available, full participation is always optimal. The reason is that informational punishment threatens deviators with a lottery over choice sets in case they veto a mechanism. That threat is sufficient to ensure full participation.

Proposition 2. *It is without loss of generality to focus on SSOs that imply full participation when informational punishment is available.*

The formal argument is constructive and relegated to the appendix. To gain intuition, suppose informational punishment is not available. Furthermore, assume there is an allocation that can only be achieved if firm i vetoes the mechanism on the equilibrium path.

[15] Naturally, the revelation principle for the grand game holds. This is the case, however, because firms are forced to participate by modeling assumption.

Fixing the choices of all other firms, firm i's decision provides two information structures. These are I^V, the information structure after i's veto, and $I^{V\setminus i}$, the information structure after i's acceptance. By Bayes' plausibility, the prior is an *expansion* of the two information structures in the sense of Bergemann and Morris (2016). The only reason why a veto by firm i may be desired is that the resulting partitioning of the information deters some type θ_j of some firm j from vetoing.

Provided that all *participating* firms report truthfully, the signaling device Σ replicates the partitioning of information. That is, firm j contemplating a veto faces (in expectations) the same situation as when firm i vetoes the SSO on the equilibrium path. Truthful reporting to Σ is incentive compatible for any firm and no firm expects to observe a veto on-path. There always exists an off-path belief in which participating firms ignore the realization about the deviator's type (e.g. because they assume a double deviation took place). Thus, Σ is incentive compatible.

Two additional aspects are worthwhile to keep in mind. First, the full-participation result is independent of the designer's objective. That is, informational punishment implies that any implementable outcome is implementable using an SSO with full participation. Second, any firm's veto decision is binary. Therefore, it suffices that the signal realization about any firm is binary too. Since the number of firms is finite, so is the total number of possible signal realizations. Thus, even if types are continuously distributed signal realizations are finite.

A potential concern for the relevance of Proposition 2's result is that we assume that the designer can freely pick off-path beliefs under the perfect-Bayesian-equilibrium restriction. She can select any first-node off-path belief of the continuation game. Depending on the context and the application, such an equilibrium selection may not be reasonable. Using a refinement could instead make on-path vetoes unavoidable because it limits the designer's equilibrium choice set in the first place.[16]

Our second finding is that the result of Proposition 2 is robust to most common refinements. Specifically, whenever we refine the the equilibrium concept according to

$$(\star) \in \{\text{Perfect Sequential Equilibrium, Intuitive Criterion, Ratifiability}\},$$

then full participation remains optimal.

Proposition 3. *Suppose the solution concept is perfect Bayesian equilibrium with refinement concept* $(\star)$*. It is without loss of generality to focus on SSOs that imply full participation when informational punishment is available.*

Proposition 2 and 3 offer an alternative view on the benefits of persuasion. The classical approach of Kamenica and Gentzkow (2011) is to set up a device that produces a Bayes plau-

[16] Correia-da-Silva (2017) provides additional discussions on this issue and how it may interfere with the design of a mechanism.

sible signal to influence the agent's action. Instead, the informational-punishment approach is to produce a Bayes' plausible signal that is relevant only if agents do *not* take the desired action, i.e., veto the designer's proposal. Thus, agents are indirectly persuaded. We have shown that informational punishment can at least replicate any outcome that is achieved by an on-path veto, and thus overcomes the participation issue. Thus, Proposition 2 and 3 simplify the characterization of veto-constraint problems, stating that any optimal solution involves full participation.

For the special case that the designer can propose any game, Proposition 2 implies that the revelation principle holds. That is, any outcome of the grand game can be represented by a direct-revelation mechanism that is accepted by all parties. Celik and Peters (2011) show that the same is not true absent informational punishment. Restoring the revelation principle increases the tractability of the (mechanism-)design problem as classic solution methods apply directly under the revelation principle.

Properties of Informational Punishment

In this part we state and discuss properties of informational punishment. We start by a simple corollary to Proposition 2 which shows that firms' privacy is kept almost surely despite informational punishment.

Corollary 1 (Privacy)**.** *On the equilibrium path no signal realization is disclosed.*

Privacy concerns are often reported to be an obstacle to participation. Informational punishment is a tool to distribute information, and may thus worsen privacy concerns. In contrast, we show that the participation decision becomes uninformative because all types pool by participating in the mechanism. Moreover, while informational punishment threatens to release information, the actual realization becomes public in zero-probability events only.

The second corollary to our results concerns the question when informational punishment strictly increases the set of implementable SSOs. It follows from Jensen's inequality.

Definition 1 (Demanding Participation Constraints)**.** The participation constraint of type θ_i of firm i is *demanding* if the value of vetoing $v_i(\theta_i)$ is strictly concave in I in some neighborhood around the prior I^0.

Corollary 2. *Informational punishment strictly increases the set of implementable SSOs if and only if the participation constraint is demanding for some type θ_i.*

We conclude this section by establishing a condition on the implementability of a given SSO. The condition shows that informational punishment transforms the environment but has no direct influence on the mechanism itself. To avoid measurability issues we assume a finite type space.[17]

Moreover, we allow the signaling device to condition its realization on the *vetoing firm*. We refer to this type of informational punishment as *directed informational punishment*. Directed informational punishment Σ is a collection of random variables $\Sigma_i^V(m_i)$ where $V \in \mathcal{N}$.

To proceed, consider any decision rule π_{I^0} associated with some $\pi \in \Pi$. Let $U_i(\theta_i)$ be type θ_i's on-path expected utility from π_I^0. Define the function $\omega_i(I;\theta_i) := v_i(\theta_i, I, \pi_I^M) - U_i(\theta_i)$, its maximum over possible types $\overline{\omega}_i(I) := \max_{\theta_i} \omega_i(I;\theta_i)$, and a convex closure.

Definition 2 (Convex Closure)**.** The convex closure, $co(f)$, of a function f is the largest convex function that is (pointwise) smaller than f.

$$co(f(x)) := \sup\{g(x) : g(x) \leq f(x) \text{ and } g \text{ convex}\}.$$

We state a sufficient and a necessary condition for the implementability of an SSO. If these conditions coincide they provide a full characterization of the implementable set.

Proposition 4. *Consider an environment* (Θ, I^0, Π^M) *with* Θ *finite. The SSO* π_{I^0} *is implementable with directed informational punishment*

- if *for every* i *and some firm-dependent veto information structure* I^i*:* $co(\overline{\omega}_i(I^i)) \leq 0$.
- only if *for every* i *and* θ_i*, and some firm-dependent veto information structure* I^i*:* $co(\omega_i(I^i;\theta_i)) \leq 0$.

Informed-Principal Problems

Often, standards are set *by one of the firms*. That is, instead of being available at the beginning of the grand game, some firm proposes the SSO at an interim state, that is, after the firm is aware of its own type. Patent pools being set up around key patents of a dominant firm are an example of such SSOs.

Formally, instead of a non-strategic third-party, one of the firms, say $i = 0$, proposes a mechanism as alternative to the market solution. The setting becomes an informed-principal problem. Firms $i = 1, ..., N$ are the agents.

A key concept to solve informed-principal problems is the concept of inscrutability (see Myerson, 1983). It states that it is without loss to assume that the informed principal, firm 0, selects a mechanism that does not allow the other firms $1, ..., N$ to learn about the principals type from the proposed mechanism. That is, inscrutability means it is without loss to restrict

[17] A finite type space avoids concerns about the non-existence of the optimal signaling device. Determining the optimal device with continuous types is possible but notationally tedious. Courty and Ozel (2017) provide an approach to solve for optimal signals with continuous type spaces. See also Gentzkow and Kamenica (2016).

attention to pooling solutions of the grand game. In a pooling equilibrium, each principal type proposes the same mechanism.

The market solution can depend non-linearly on beliefs about firm 0's type. Consequently, the principle of inscrutability might fail. Firm 0 may have strict incentives to signal its private information via the mechanism proposal. Thereby it relaxes the other firms participation constraints. Our next result states that these concerns are irrelevant if informational punishment is available.

Proposition 5. *If a principal has access to informational punishment, then the principle of inscrutability holds.*

Informational Opportunism

So far we assumed that the signal's designer is impartial and commits to a signaling function *before* receiving the firms' reports. In some applications this assumption may be too demanding. If the designer of the signaling device is itself a strategic player, it may be hard for her to commit to both a certain signal structure and to report its outcome. Absent commitment the problem of informational opportunism introduced by Dequiedt and Martimort (2015) becomes a concern.

Suppose an SSO is vetoed. Two aspects are important. First, how large is the designer's commitment power? Second, does the designer's objective change, that is, is it credible for her to punish the deviating firm?

An extreme form of informational opportunism occurs if the signal's designer chooses the *signal realization*, σ, rather than the *signaling device*, Σ. In that case, the designer cannot commit to a mapping from reports to realizations, but simply makes a public announcement. A designer who cannot commit to a signaling device at any point is often useless. In turn, the results of Proposition 2 to 5 trivially do not hold, even if the designer wants to *punish the deviator*.

Instead we focus on a designer whose action space is still the set of signaling devices. We make the following assumption.

Assumption 1 (No Fabricated Data)**.** The choice of signaling device, Σ, becomes public together with its realization, σ.

Under Assumption 1 the designer can back up her claims by providing evidence. Indeed, all interested parties can see the designer's method to reach her conclusion, σ. Within this setting, informational opportunism is best seen when considering the timing of the grand game. In our baseline model the designer commits to Σ *before* firms' decided about vetoing. She is thus an impartial third-party and not an interested player in the grand game. Now, in contrast, we assuming that the designer is an interested player in the game.

First, we assume that the designer can commit to punish a potential deviator. However, she *cannot* commit to her signaling device at the beginning of the game. Instead she picks Σ after having elicited the types from the firms, and firms have made their acceptance decision. That is, the designer faces *ex-post incentive constraints.*

Definition 3 (Informational Opportunism)**.** The designer of the signaling device suffers from *informational opportunism* if she cannot commit to a signaling device Σ before players' participation decision.

We are interested in situations in which the designer is *immune* to informational opportunism. In these situations the results of our baseline model also hold under informational opportunism.

Definition 4 (Immunity)**.** A result is *immune to informational opportunism* if it is implementable by a designer that suffers from *informational opportunism.*

Allowing for informational opportunism comes at a cost and we cannot make a general statement on immunity. However, we state a set of definitions to restrict the environment. These restrictions allow us to state Proposition 6 which determines a sufficient condition for immunity.

To implement a certain signaling device under ex-post incentive constraints of the designer, it is useful to identify the designer by her *type*, that is, by the information she elicited from the (participating) firms. Observe that any designer type *could* fully reveal her type by the choice of the appropriate signaling device.

Yet, if the designer chooses not to reveal her type, the interpretation of realization σ depends not only on Σ. It also depends on the belief that firms form about the designer's type when observing Σ. Thus, each Σ triggers a belief which, together with Σ, leads to a lottery over information structures. For a given designer's objective, different types may have different preference rankings over lotteries. We assume, however, that preference are aligned and all types share the same ranking. Thus, there is a common understanding which information structures are better to achieve the desired goal.

To achieve immunity to informational punishment we impose two properties on the environment. Independently distributed types of the firms and aligned preferences.

Definition 5 (Aligned Preferences)**.** Fix arbitrary distributions over a collection of $(N-1)$ firms' types. Let F and F' be two (possible) distributions of the remaining firm i's type. The designer types' preferences are aligned if whenever F first-order stochastically dominates F' every designer type prefers F to F'.

Finally, we define an extreme notion of the desire to separate.

Definition 6 (Unraveling Pressure)**.** A designer faces unraveling pressure under signaling device Σ if she strictly prefers to verify her type to the lottery induced by Σ.

Proposition 6. *Suppose firms' types are independently distributed and the designer's preferences are aligned. A signaling device* Σ *is implementable under informational opportunism if and only if no type faces unraveling pressure.*

The intuition behind Proposition 6 is that if firms face no unraveling pressure, they have no incentives to fully disclose the information they hold. In that case, firms' updating after observing a deviation, Σ', from the promised protocol depends on the signal realization and on firms' (off-path) belief about the designer's type when observing a deviation. If the designer's types preferences are aligned, they share a common worst information structure given Σ'. That information structure can be induced by adjusting firms' off-path beliefs. The only option for a designer to secure herself against such a worst information structure is to fully verify her type. If she prefers not to do that under Σ, Σ is immune to strong informational opportunism. If the conditions of Proposition 6 are met, immunity follows.

Corollary 3. *Suppose firms' types are independently distributed and the designer's preferences are aligned. Proposition 2 to 5 are immune to informational opportunism.*

In the setting of Section 2, all these conditions are met. Further, whenever the designer's objective function is concave, immunity is guaranteed. Concavity of the objective function implies that the (ex-ante) optimal signaling device leads to unraveling. Thus, by construction no type faces unraveling pressure and Proposition 6 applies.

Corollary 4. *Suppose firms' types are independently distributed and the designer's preferences are aligned. A signaling device is immune to informational opportunism if the designer's objective is weakly concave in the information structure.*

Weaker forms of informational opportunism might be relevant too. In particular, the designer may be able to commit to an investigation Σ, but may choose to conceal the outcome of her investigation. We refer to this as weak informational opportunism.

Definition 7 (Weak Informational Opportunism)**.** The designer of the signaling function Σ suffers from *weak informational opportunism* if she can commit to a signaling function Σ at the beginning of the game, but not to the disclosure of the realization σ.

Corollary 5. *Suppose firms' types are independently distributed and the designer's preferences are aligned. Proposition 2 to 5 are immune to weak informational opportunism.*

Finally, the designer may suffer from weak informational opportunism *and* may not be able to commit herself to punish firms after a veto. That is, firms are (ex-ante) ambiguous about the designer's objective once the SSO breaks down. It turns out that the results from Proposition 2 to 5 continue to hold in this case, making informational punishment robust against both ambiguity and weak informational opportunism.

Corollary 6. *Suppose firms' types are independently distributed and the designer's preferences are aligned. If Proposition 2 to 5 are immune to weak informational opportunism even when ambiguous about the designer's objective function.*

Indeed, if the designer's types preferences are aligned, Σ has an common worst signal realization. Not revealing the signal realization leads to an off-path belief. For given objective of the designer, that off-path belief puts all probability mass on the worst signal.

4 Discussion

In this section we discuss our most crucial assumptions and their implications for our results.

Public Vetoes. The most crucial assumption is that firms can publicly veto a mechanism. An important consequence of this public veto ability is that the mechanism's power in the event of a veto is limited. Public vetoes imply that firms learn who vetoed and who ratified the mechanism.

An alternative assumption is that firms learn that the mechanism is void, but do not learn why. Such settings are modeled as "trembling mechanisms" in Gerardi and Myerson (2007) and Correia-da-Silva (2017). A trembling mechanism "fails" with positive probability although all parties vow to cooperate. Failure of the mechanism is an on-path event and the designer can arbitrarily influence the information structure via the trembling function.

In our setting trembling mechanisms do not improve. This is the case, because we assume each firm can verify its acceptance decision. The ability to verify the participation decision increases firms' bargaining weight at the acceptance stage of the mechanism. If firms are able to observe attendance of others, a tremble is identified as such. Thus, firms can distinguish between on-path trembles and off-path vetoes. In addition, using trembles implies that cooperation fails inefficiently often. This leads to an efficiency cost—even if this cost is small. In contrast, informational punishment operates more subtle affecting off-path events only.

Processing Information. Meanwhile we assume that firms cannot commit at any point in time to ignore publicly available information. A deviator that commits to ignore news arrival is immune to informational punishment. However, once a veto is observed and the signal has been generated, it is in any firms interest to learn the information the signal provides. Moreover, it is sufficient that the non-deviating firms *believe* that the deviator reacts to information to make informational punishment work. We are confident that commitment to ignore news arrival is hard to sustain. Indeed, ignoring information is never part of any continuation equilibrium. If a firm is expected to ignore information, this information becomes non-strategical. Thus, the firm has an incentive to learn the information.

Privacy Concerns. We assume that the signaling device is impartial and can be trusted to conceal information. If that assumption is satisfied, full participation can be sustained at no cost. In fact, the signaling device is incentive compatible, needs no information on its own, and cannot directly influence any firm's behavior at any time. Moreover, since signals do not realize on the equilibrium path, the signaling device serves as a pure threat and privacy considerations should play no role.

5 Conclusion

We consider an SSO seeking to determine a standard in an industry. In that setting informational punishment can be a powerful tool to discipline privately informed firms to cooperate on setting the standard. That way, the likelihood of a standard war can be severely reduced or even completely avoided.

We model informational punishment as trustworthy signaling device. The device elicits information from participating firms. It releases a noisy signal of this information if firms fail to coordinate on a mechanism. We show that the threat of the signal realization relaxes firms' participation constraints and guarantees full participation.

Our model contributes to the discussion whether "it's always good to talk" even if the outside option is lucrative. We show that talking to an impartial third party is sufficient to sustain some cooperation, if that third party promises to "talk back" in case firms cannot coordinate on a form of cooperation.

Our findings offer several interpretations on real-world phenomenons. For example, they can rationalize the existence of news leaking platforms. Providing such platforms with information can, perhaps, be understood as way to create a signaling device that helps to sustain coordination. In addition, risky product announcements that potentially turn into vaporware are a form of informational punishment. Through the announcement a firm commits to releasing an informative signal in the future. That way, competing firms can be persuaded to cooperate on setting a standard. Moreover, informal information exchange at industry conventions may be seen as a way to credibly distribute information such that competing firms correctly expect the realization of a signal in case they refuse to cooperate.

Methodologically, our approach restores classic results such as the revelation principle with full participation and the principle of inscrutability. It allows for tractable solutions in a variety of applied problems beyond SSOs. Veto mechanisms and Bayesian games as outside options are present in many areas of industrial organization and law and economics. In addition, they are relevant in the problem of political bargaining in the shadow of a popular vote, or in financial markets when creditors decide whether to act jointly or independently if the borrower is in distress.

Informational punishment increases the outcomes competitors can coordinate on. Thus, when evaluating the potential of cooperation among competitors, a regulator should carefully consider whether informational punishment is available to firms.

A Proofs

Proof of Lemma 1

Proof. The proof is an application of Siegel (2014). We defer it to appendix B.

□

Proof of Proposition 2

Proof. The proof is constructive. Take any SSO π, and an equilibrium in which the SSO is vetoed with positive probability on the equilibrium path. We call this the veto equilibrium. We first characterize the decision rule induced by the play of the veto equilibrium. Then, we show that there is an SSO which is unanimously accepted and leads to the same decision rule.

Firms might randomize their veto decision. Let $\xi(\theta)$ be the probability that π is vetoed given type profile θ. Moreover, $\xi_i(\theta_i)$ is the likelihood that type θ_i of firm i vetoes π on the equilibrium path. The set of firms that vetoed, V, might be random. After the veto decision, firms observe the set of firms that vetoed, say V_k, and update to information structure I^{V_k}, and outcomes realize according to $\pi^M_{I^{V_k}}$. Taking expectations over all possible realizations of V, V_k, the ex-ante expected continuation game conditional on a veto is a lottery $(P(V_k), \pi^M_{I^{V_k}})$ defined over all V_k. $P(V_k)$ is the on-path likelihood that a veto is caused by the set V_k and not by any other set of vetoing firms. Because $\Pi^M \in \Pi$ and Π is closed under convex combinations, the lottery leads the decision rule $\pi^M_{I^{\mathbb{E}V_k}} = \sum P(V_k)\pi^M_{I^{V_k}} \in \Pi$.

Conditional that no firm vetoes, the information structure is I^a, and π_{I^a} is the associated decision rule.

The grand game implements an I^0-IC decision rule $\pi'_{I^0} := \xi\pi^M_{I^{\mathbb{E}V_k}} + (1-\xi)\pi_{I^a}$. Again, $\pi' \in \Pi$ because Π is closed under convex combinations.

We now construct a signaling device Σ such that the SSO π'_{I^0} is implementable under full participation. By construction, π' is feasible and π'_{I^0} is incentive compatible. What remains is to show that no firm has an incentive to veto π'_{I^0}.

We construct the following signaling device $\Sigma_i : \Theta_i \to \Delta(\{0,1\})$ where $\sigma_i(\theta_i) = 1$ with probability $\xi_i(\theta_i)$ and 0 otherwise. When observing off-path behavior (i.e., a veto) by firm i, firm j believes that firm i randomized over the entire type-space when reporting to Σ_i. Thus, she disregards the realization σ_i. Further, we choose the off-path belief on i identical to the belief that firms attach to firm i after observing her unilateral veto in the veto equilibrium.

No firm i has an incentive to veto the mechanism. If a firm vetoes the SSO the signals Σ_i provide her with the same lottery over information structures that she expects from a veto in the veto equilibrium. Participation, in turn, gives the same outcome as the veto equilibrium. No player can improve upon the outcome of the veto equilibrium by vetoing π'.

Finally, truthful reporting to Σ_i is a best response as Σ_i is payoff irrelevant on the equilibrium path. Thus, under (π', Σ) an equilibrium with full participation in π' exists that implements the same outcome as the veto equilibrium. □

Proof of Proposition 3

Proof. Ratifiability requires full participation in the mechanism and therefore holds trivially, as the designer can always choose a degenerate signaling device. It thus is without loss of generality to show full participation under refinement $(\star)' \in$ {Perfect Sequential Equilibrium, Intuitive Criterion}.

Consider the veto equilibrium used in the proof of Proposition 2. Suppose this equilibrium satisfies refinement $(\star)'$.

We show that the full-participation equilibrium constructed in the proof of Proposition 2, (Π', Σ), satisfies the same refinement criterion. Two aspects are crucial. First, compare the equilibrium with vetoing and that with full participation. On-path (expected) outcomes and those outcomes that are off-path but can be reached by a unilateral deviation are identical between these two equilibria for every state θ. Thus, in any state θ in which the mechanism is unanimously accepted in both equilibria, both outcomes coincide and so does the credibility of the beliefs. Second, consider a state θ in which the mechanism is rejected in the veto equilibrium with positive probability. Now, for the same state, suppose that Π' is rejected in the full-participation equilibrium, which is an off-path event. The resulting *off-path belief* on the deviator θ_i coincides with the *on-path belief* on the same θ_i in the veto equilibrium. Thus, the constructed off-path beliefs put positive mass only on those types that *weakly prefer to deviate*, while obviously no such type *strictly prefers to deviate*. Thus, any off-path belief for type θ_i is credible in the sense of Grossman and Perry (1986) *and* off-path beliefs do not violate the intuitive criterion. □

Proof of Proposition 4

Proof. Because Θ is finite any information structure is a finite dimensional matrix. Because informational punishment is directed, it suffices to consider the veto of a single firm i.

Any realization of σ after i vetoes induces $\omega_i(I^{i,\sigma}, \theta_i)$. Given I^i, any signaling device Σ induces a lottery over belief systems with $E_\sigma[I^{i,\sigma}] = I^i$. Fix any function ω. By Jensen's inequality a Σ exists such that $E_\sigma[\omega(I^{i,\sigma})] < \omega(E_\sigma[I^{i,\sigma}])$ if and only if $\omega(I)$ is concave in some neighborhood of I^i. $co(\omega(I))$ is the the largest function smaller than ω that is not concave in some neighborhood of I^i.

We first show sufficiency. If $co(\overline{\omega}_i(I^i)) \leq 0$ there is a signal such that $0 \geq E_\sigma[\overline{\omega}_i(I^i)] = \sum_\sigma Pr(\sigma) \max_{q \in \Theta_i} \omega_i(I^{i,\sigma}, q) \geq \sum_\sigma Pr(\sigma) \omega_i(I^{i,\sigma}, \theta_i)$ for any $\theta_i \in \Theta_i$.

For the necessary part take any type for which $co(\omega_i(I^i, \theta_i)) > 0$. Then $E_\sigma[\omega_i(I^{i,\sigma}, \theta_i)] \geq co(\omega_i(I^{i,\sigma}, \theta_i)) > 0$ for any Σ. Thus, π_{I^0} cannot be implemented with full participation. □

Proof of Proposition 5

Proof. Suppose there exists an equilibrium of the grand game such that different types of firm 0 propose different πs. Let $\mathcal{M}$ be the set of πs that are proposed with strictly positive probability. Let $\xi_0^\pi(\theta_0)$ denote the probability that firm 0 type θ_0 proposes mechanism $\pi \in \mathcal{M}$.

Consider the case in which at least one type of one firm vetoes at least some $\pi \in \mathcal{M}$ on the equilibrium path. We refer to this equilibrium as the separate-and-veto equilibrium. Recall that, if π is vetoed, some rule in Π^M results. Let the probability that π is vetoed be ξ^π. Moreover, $\xi_i^\pi(\theta_i)$ is the probability that θ_i vetoes π. The separate-and-veto equilibrium implements a I^0-IC decision rule, $\pi_{I^0}^E$. $\pi_{I^0}^E \in \Pi$ because Π is closed under convex combinations.

We prove existence of the following equilibrium. All types of firm 0 propose $\pi_{I^0}^E$ and every firm accepts it. This equilibrium leads to the I^0-IC decision rule $\pi_{I^0}^E$.

We construct a signaling device Σ to support acceptance of $\pi_{I^0}^E$. Let $o : \mathcal{M} \to \mathbb{R}$ be some invertible function. For $i = 0$, we construct the signal $\Sigma_0(\theta_0)$ with support $\{o(\Pi')\}_{\Pi' \in \mathcal{M}}$ and associated probabilities $Pr(\Pi'|\theta_0) = \xi_0^{\Pi'}(\theta_0)$. For any $i > 0$, let the signal be $\Sigma_i(\theta_i) = 1$ with probability $\xi_i(\theta_i)$ and $\Sigma_i(\theta_i) = 0$ with remaining probability. Whenever firm $i > 0$ vetoes, a signal realizes according to Σ. Thus, the reason why no firm rejects Π^E is the same as in the proof of Proposition 2. The only difference is that the signaling function also replicates the potential signal-by-mechanism-choice behavior of the principal, captured by Σ_0. □

Proof of Proposition 6

Proof. Consider a signaling device Σ. Assume firm i has vetoed the mechanism. The designer elicited the information θ_{-i} from the non-deviating firms. We want to show that no designer type, θ_{-i}, has an incentive to announce a different device than Σ.

Suppose type θ_{-i} deviates by announcing Σ' which does not verify θ_{-i}. Firms observe the deviation Σ' and its realization σ'. Using these objects, they form off-path beliefs about the types of all $N-1$ firms. The symmetry of PBE together with the independence of firms' types implies that any subset of firms has identical beliefs about the firms not in that subset.

The off-path beliefs on the designer's type are therefore only restricted by the signaling function Σ'. If a realization σ' occurs with probability 0 given a type θ_{-i}, then firms exclude that type from the set of possible designer types. Denote the set of not excluded types by $\Theta^{\sigma'}$. The distribution $F^{\sigma'} : \Theta^{\sigma'} \to [0, 1]$ is arbitrary. That is, for every Σ' there always exists an off-path belief about the deviating designer that rationalizes $F^{\sigma'}$.

By assumption Σ' does not verify θ_{-i}. Thus, $|\Theta^{\sigma'}| > 1$. Because types have aligned preferences we can find a type $\tilde{\theta}$ such that a degenerate belief on $\tilde{\theta}$ makes every type other than $\tilde{\theta}$ worse off compared to revealing her own type. Thus, no unraveling pressure implies that no type benefits from the deviation. Hence Σ is implementable under informational opportunism. □

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Online Appendix

B All-pay Auction with binary types and Proof of Lemma 1

Outline. We first state and proof the equilibrium strategies and payoffs in the all-pay auction. For completeness we provide the arguments taken from Siegel (2014) thereafter.

Equilibrium Strategies and Expected Payoffs in the All-Pay Contest

We first characterize the firm's equilibrium strategies which imply the equilibrium payoffs.

Consider an all-pay contest with minimum investment r, and an environment in which firm i might have marginal cost 1 or $k > 1$. From firm $-i$'s point of view i has marginal cost 1 with probability p_i. Let $\Delta_i := \frac{1-p_i}{k}$ and assume the commonly-known information set I lies in $\mathcal{I}$. Then, the equilibrium takes the following form, depending on I:

Lemma 4. If $I \in \mathcal{I}_0$,

- *Player 1 and 2, type k, invest zero,*
- *Player 1, type 1, uniformly mixes on $(r, 1]$ with density $\frac{1}{p_1}$ and invests r with probability $1 - \frac{1+r}{p_1}$*
- *Player 2, type 1, uniformly mixes on $(r, 1]$ with density $\frac{1}{p_2}$ and invests zero with probability $1 - \frac{1+r}{p_2}$.*

The expected interim utilities of each firm and type are 0.

If $I \in \mathcal{I}_A$,

- *Player 1 and 2, type k, invest zero,*
- *Player 1, type 1, uniformly mixes on $(r, p_2 + r]$ with density $\frac{1}{p_1}$ and invests r with probability $1 - \frac{p_2}{p_1}$*
- *Player 2, type 1, uniformly mixes on $(r, p_2 + r]$ with density $\frac{1}{p_2}$.*

The expected interim utilities of each firm and type are given by

$$V_i(1) = 1 - r - p_2,$$
$$V_i(k) = 0.$$

If $I \in \mathcal{I}_B$,

- *Player 1, type k, invests r*
- *Player 1, type 1, uniformly mixes on $(r, \Delta_2]$ with density $\frac{k}{p_1}$, on $(\Delta_2, \Delta_2 + p_2]$ with density $\frac{1}{p_1}$ and invests r with probability $1 - \frac{1-rk}{p_1}$.*
- *Player 2, type k, uniformly mixes on $(r, \Delta_2]$ with density $\frac{1}{1-p_2}$ and invests zero with probability $1 - \frac{1}{k}\left(1 - \frac{r}{\Delta_2}\right)$.*
- *Player 2, type 1, uniformly mixes on $(\Delta_2, \Delta_2 + p_2]$ with density $\frac{1}{p_2}$.*

The expected interim utilities of each firm and type are given by

$$V_i(c_l) = \Delta_2(k-1),$$

$$V_1(k) = (\Delta_2 - r)(k-1),$$
$$V_2(k) = 0.$$

If $I \in \mathcal{I}_C$,

- *Player 1, type* k*, uniformly mixes on* $(r, \Delta_1]$ *with density* $\frac{1}{\Delta_1}$ *and invests* r *with probability* $\frac{r}{\Delta_1}$
- *Player 1, type* 1*, uniformly mixes on* $(\Delta_1, \Delta_2]$ *with density* $\frac{k}{p_1}$*, on* $(\Delta_2, \Delta_2 + p_2]$ *with density* $\frac{1}{p_1}$.
- *Player 2, type* k*, uniformly mixes on* $(r, \Delta_1]$ *with density* $\frac{1}{\Delta_2}$ *on* $(\Delta_1, \Delta_2]$ *with density* $\frac{1}{1-p_2}$ *and invests zero with probability* $(\Delta_2 - \Delta_1)\frac{k-1}{(1-p_2)} + \frac{r}{\Delta_2}$.
- *Player 2 type* 1*, uniformly mixes on* $(\Delta_2, \Delta_2 + p_2]$ *with density* $\frac{1}{p_2}$.

The expected interim utilities of each firm and type are given by

$$V_i(c_l) == \Delta_2(k-1),$$
$$V_1(c_h) = (\Delta_2 - \Delta_1)(k-1),$$
$$V_2(c_h) = 0.$$

Proof. The equilibrium construction in each case follows essentially that of Siegel (2014).

By Proposition 2 in Siegel (2014) it is without loss of generality (in terms of the outcome) to restrict ourselves to constructing one equilibrium as all equilibria are payoff equivalent.[18]

Let e_i be the chosen investment of firm i. Given the strategies of its opponent, σ_{-i} and the information structure I, firm i , type c_l, chooses investment b_i that satisfies:

$$Pr'(b_i > b_{-i}|\sigma_{-i}, I) - c = 0.$$

Given this, strategies satisfy the local optimality condition for any information structure by construction.

Thus, what is left to prove is global optimality. This is done case by case:

Case 1: $I \in \mathcal{I}_A$

Global optimality follows from $p_1 \geq p_2 \geq 1 - rk$. If firm 1, type k invests r, it receives payoff $1 - p_2 - rk < 0$. Similarly, if firm 2, type k invests r, it receives payoff $1 - p_1 - rk < 0$. Player 2, type 1 receives payoff $(1-p_1) + (p_1 - p_2) - r$ from investing arbitrarily above r, which is the same when investing until the top of the specified interval.

Case 2: $I \in \mathcal{I}_B$

Global optimality follows from $p_1 \geq 1 - rk > p_2$. If firm 1, type k invests r, it receives payoff

$$V_1(k) = (1-p_2)\frac{(k-1)(1-p_2) + rk}{k(1-p_2)} - rk =$$
$$\frac{(k-1)(1-p_2) + rk - r(k)^2}{k} =$$
$$\frac{(k-1)(1-p_2) - rk(k-1)}{k} =$$

[18]See below for the respective argument.

$$(k-1)(\Delta_2 - r)$$

which is larger than 0. Investing above $r+\epsilon$ instead of r increases firm 1's probability to win by $(1-p_2)\frac{1}{1-p_2}\epsilon$ at the cost of $k\epsilon$, which is negative since $k>1$. By construction, firm 2, type k is indifferent between investing arbitrarily larger than r and zero, since any investment $b \in (r, \Delta_1)$ yields utility

$$\begin{aligned}&(1-p_1) + p_1\left(\left(1 - \frac{1-rk}{p_1}\right) + (b-r)\frac{k}{p_1}\right) - bk \\ =&(1-p_1) + p_1 - (1-rk) + bk - rk - bk = 0\end{aligned}$$

Player 1, type 1 receives payoff

$$(1-p_2)\frac{(k-1)(1-p_2)+rk}{k(1-p_2)} - r = \Delta_2(k-1)$$

from investing r, which is the same when investing until the top of the specified interval. Player 2, type 1 receives payoff

$$(1-p_1) + p_1(1 - \frac{p_2}{p_1}) - \Delta_2 = \Delta_2(k-1)$$

from investing the lower bound of the specified interval. This is the same payoff he receives when investing the upper bound of the specified interval.

Case 3: $I^i \in \mathcal{I}_C$

Global optimality follows from $1-rk > p_1 \geq p_2$. If firm 2, type k invests r, it receives payoff

$$V_2(k) = (1-p_2)\frac{(k-1)(p_1-p_2)+rk^2}{k(1-p_2)} - rk = (p_1-p_2)\frac{k-1}{k} \geq 0.$$

By construction, firm 2, type k is indifferent between investing arbitrarily larger than r and zero:

$$(1-p_1)\frac{rk}{1-p_1} - rk = 0$$

Player 1, type 1 receives payoff

$$(1-p_2)(1-(\frac{p_1-p_2}{k}\frac{1}{1-p_1})) - \Delta_1 = \Delta_2(k-1)$$

from investing Δ_1, which is the same when investing until the top of its specified interval. Player 2, type 1 receives payoff

$$(1-p_1) + p_1(1-\frac{p_2}{p_1}) - (\Delta_1 + \frac{p_1-p_2}{k}) = \Delta_2(k-1)$$

from investing the lower bound of the specified interval. This is the same payoff it receives when investing the upper bound of the specified interval.

□

Adaptation of the Siegel (2014) framework

Outline. We proceed using the following steps. First, we restate central arguments of the all-pay auction from Siegel (2014) adapted to our notation. Second, we restrict the set of possible equilibrium outcomes using these arguments. Third, we establish piecewise linearity. Then, we characterize the different regions.

Lemma 5 (Siegel (2014))**.** *In a 2-firm all-pay contest with finite, independently drawn types and a minimum investment the following statements hold:*

(i) Every equilibrium is monotonic. All monotonic equilibria are payoff equivalent.

(ii) There is no positive investment level at which both firms have an atom. If a firm has an atom, the atom is either at 0 *or* r*.*

(iii) If some investment level strictly above r *is not a best response for any type of one firm, no weakly higher investment level is a best response for* any *firm.*

(iv) The intersection of the equilibrium investment levels of two different types of the same firms is at most a singleton.

(v) No firm ever invests more than $1/c_i$*.*

Proof. See Lemma 1 and 2 in combination with Proposition 2 in Siegel (2014). □

By (i) it suffices to characterize one equilibrium. (ii) implies that some firm and some type earns 0 profits. The fact that types are ordered implies that it is a type-k cost firm. By (iii) the two type-1 cost firms have the same upper bound on their equilibrium investment levels and thus the same payoffs. Finally, (iv) together with (iii) implies that it is sufficient to characterize the positive investment strategies up to a constant, as there are no "holes." Together with (ii), firms' equilibrium strategies are distributions with support on $0 \cup (r, \bar{b}]$ for some $\bar{b}$. Firms don not have a mass point on $(r, \bar{b}]$. Moreover, $\bar{b} \leq 1/c_i$ where the last inequality follows from (v).

Consider such an equilibrium for any information structure I. Take any two levels b_i and b_i' in type c_i's equilibrium support. Optimality requires

$$\frac{Pr(b_i > b_{-i}|I) - Pr(b_i' > b_{-i}|I)}{(b_i - b_i')} = c_i. \tag{3}$$

Thus, firm $-i$'s equilibrium investment distribution is differentiable with constant density. Let $F_{-i,c_{-i}}$ denote type c_{-i}'s cumulative distribution function, then $Pr(b_i > b_{-i}|I) = p_{-i}F_{-i,1}(b_i) + (1-p_{-i})F_{-i,k}(b_i)$. By property (iv) of Lemma 5 either $F_{-i,1} = 0$ or $F_{-i,k} = 1$ and by (iii) and Equation (3) the density at the highest equilibrium investment level is $f_i = 1/p_i$. The same holds true for any part of the intersection of the equilibrium support of the cost-1 types of firm 1 and 2.

We can now characterize the different regions. Take region 0, i.e., $r > 1 - p_2$. The likelihood that firm 2 invests on the interval $(r, 1]$ is smaller than 1. Thus, by (v) and (ii) of Lemma 5 it has an atom at r or 0. Since $p_1 > p_2$ the same holds for firm 1. Yet, by (ii) *some* firm has an atom at 0. Thus, by (iii) rents are fully dissipated.

In region A we have that $r < 1 - p_2$. Firm 2 type 1 invests on the interval $(r, \bar{b}]$ for some $\bar{b} < 1$. At the same time $r > (1 - p_2)/k$ such that firm 2 type k can be successfully deterred. Only type-1 cost firms invest a positive amount and firm 1 uses its residual mass for investment at r, it wins with the likelihood that firm 2 is the k-cost type. Both type-1 cost firms make (the same) positive profits, type-k cost firms make no profit.

In region B the minimum investment is low enough such that a type-k cost firm 1 investing r would make positive profits if type-k cost firm 2 remains out of the contest, but not vice versa. Thus, both type-k cost firms cannot be deterred from the contest. In equilibrium all types and firms participate. Firm 1 has an atom at r and firm 2 has an atom at 0. Consequently all but type-k cost firm 2 expect positive profits. The expected payoff becomes less responsive to changes in p_2 because type-k cost firm 2 is expected to invest a positive amount, (iv) provides the remaining argument.

Finally, in region C, firm 2's incentives to participate increase (compared to region B) as firm 1 becomes ex-ante weaker. In response type-k cost firm 1 increases its expected investment which decreases its expected payoff. As p_i goes to 0 both high cost participants increase their investment until at $p_i = 0$ payoffs reach the familiar complete information result of full rent dissipation.