Persuading to Participate: Coordination on a Standard*

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Abstract

We study coordination among competitors in the shadow of a market mechanism. Our leading example is that of standard setting: firms either coordinate 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. Several business practices can serve as informational punishment. Informational punishment is robust to relaxing commitment assumptions.

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1 Introduction

The road to the standard for high-density data discs (DVD) was not straightforward. 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.

Mutual optimism occurs if both parties receive 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. Mutual optimism implies 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 implementation 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 credible. 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.[1]

Eventually, most industries operating in two-sided markets 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.[2]

In this paper 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 the question *is there a simple and cost-effective way to foster coordination?* Our answer is affirmative if firms have access to a signaling device. The most important feature of that signaling device is that it can conceal information for some time before releasing it. We construct the optimal signaling device and refer to it as *informational punishment*.

Informational punishment has a variety of desirable features: (i) it respects firms privacy, that is, in equilibrium the signal realization becomes public with probability zero; (ii) a decentralized implementation is possible, that is, parties can design the optimal device themselves; (iii) it is easy to interpret, that is, it is sufficient to restrict attention to binary realizations; and (iv) it does not interfere with firms' incentives inside the SSO. We divide the analysis into two parts.

In the first part of the paper, we consider a stylized model of the standard-setting process. The model is set up to be in line with the DVD case discussed above. We construct the optimal signaling device and show how informational punishment facilitates coordination on a standard. We use our findings to relate informational punishment to several business strategies beyond those present in the DVD case. We show that apart from a neutral third party such as the TWG other buisness practices serve as informational punishment device. They include information leakage platforms and announcement of vaporware.

In the second part of the paper, we extend our insights along several dimensions. Many aspects can influence the decision whether firms join an SSO.[3] Informational

[1]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 would need to gather information from the firms.

[2]Other examples in the consumer electronics industry in which SSOs successfully managed coordination include USB and bluetooth, those that were (partially) determined through a standard war include VHS and Blue-Ray. As we will see, our theory suggests that for a rich enough contracting space, even if a standard war breaks out eventually, there is some initial coordination which is indeed what happened in the Blue-Ray case.

[3]See Baron, Li, and Nasirov (2018) and the references therein for an excellent discussion and a data

punishment is an effective tool to persuade firms irrespective of these reasons. We illustrate this point by modeling the market solution as an arbitrary game of incomplete information with an arbitrary number of firms. We define a mild minimal requirement on the set of potential SSOs the firms can select from. Under that requirement coordination on an SSO is optimal whenever informational punishment is available. In addition, we derive conditions under which informational punishment is robust to limited commitment of its designer.

While we keep the leading application of standard setting throughout the paper for consistent terminology, nothing in our model is specific to it. In fact, our findings apply to any setting in which coordination happens in light of a market solution. Examples include environmental agreements, coordination between legislators, strikes, litigation, and R&D alliences.

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. Information revelation that aims at deterring a veto of other firms is what constitutes 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 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

driven approach to disentangle the different motives.

commit to ignore public information, they update their beliefs once the information is public. They 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.

Informational punishment 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. Indeed, 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 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 can implement informational punishment. Beyond these isomorphisms, we address the role of commitment and discuss implications of informational punishment on regulators.

Related Literature. In line with Simcoe (2012) we assume that standard setting is a process in which consensus is needed to overcome the default market forces. While his focus is on bargaining under complete information, we use incomplete information as the predominant friction. Ganglmair and Tarantino (2014) also use an incomplete information framework to model bargaining in R&D. While they study cases in which private information threatens sustainability of an agreement, we study cases in which private information threatens the initial coordination on such an agreement. In a similar vein we complement Spulber (2018) who addresses the voting procedure inside organisations and how that interacts with the underlying market structure. Our model addresses an earlier stage. We are interested in *when do firms decide to join an agreement?* and *how can they convince others that coordination is better than the market?*

In our model, we adopt Farrell and Saloner (1985)'s view of a standard war as a contest between competing standards. Alternatively, firms can coordinate on an SSO that governs the patent rights.[4]

We follow Farrell and Simcoe (2012) and assume that firms can choose from a set of standard-setting organizations 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

[4]See also Besen and Farrell (1994) for an overview of this trade-off in several settings. Recently, Baron, Li, and Nasirov (2018) revisited firms' motivation of joining SSOs from an empirical perspective emphasizing the relevance of the issue.

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.

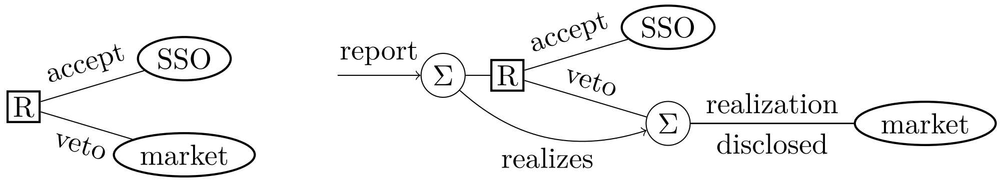
Dequiedt (2007) emphasizes the importance of non-trivial participation constraints in a model about collusion in auctions. Similar to us, he studies how participation constraints restrict the implementable allocations. The crucial difference is that in our model firms *cannot* commit to follow recommendations if coordination fails. Instead if some firm vetoes, the SSO 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 SSO itself influences these responses only indirectly through the information structure it implies *after* firms observed who has vetoed.

In our baseline model we assume that the signaling device is offered by an impartial third-party. That third-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, that is, settings in which the third-party has limited commitment.

Informational punishment applies the tools of Bayesian persuasion (see the literature following Kamenica and Gentzkow, 2011), in particular convexification (Aumann and Maschler, 1995). Our problem, however, is different 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 SSO 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 fosters coordination, and persuasion occurs "tacitly."

Gerardi and Myerson (2007) and Correia-da-Silva (2017) offer an alternative tool to induce participation. The main difference to our model is that there firms can verify neither a veto nor an acceptance decision. They 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 failure to coordinate. In our setup, trembling devices are ineffective since vetoes (or the lack thereof) are publicly verifiable. Instead, we propose informational punishment to discipline firms into participation. Different to trembling, informational punishment has no influence on the SSO itself.

The fact that full participation need not be optimal is documented in Celik and Peters (2011). We provide a simple device that makes the channel they describe disappear. Moreover, we construct the optimal device for a given set of available SSOs and provide minimal conditions on that set such that coordination is optimal.



(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 accept or veto the SSO. If they accept, 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).

We connect to our own work on information spillovers in mechanisms design (Balzer and Schneider, 2019a,b). In Balzer and Schneider (2019a) we derive a general framework to design mechanisms with information spillovers in arbitration problems. There we show how the choice of the mechanism affects the information structure and action choices *after* the mechanism is played. Here, to the contrary, we are interested in how information revelation affects decision *before* an exogenously given SSO. Balzer and Schneider (2019a) ignores these considerations by assuming a fixed outside option for each type.

In Balzer and Schneider (2019b) we address alternative dispute resolution (ADR) in legal disputes. Litigation serves both as an alternative if coordination fails or if ADR fails to settle. The model of litigation shares some similarities with the market in Section 2. Yet, there is an important difference. The litigation model in Balzer and Schneider (2019b) implies utilities that are convex in the information structure. Convexity makes informational punishment obsolete. In turn, initial participation in the mechanism is optimal even absent informational punishment. Information is relevant only *after* the mechanism. Indeed, informational punishment has no bite in both Balzer and Schneider (2019a,b): Participation constraints are *non*-demanding in the sense of Definition 2 given on page 27 in this paper.

Roadmap. The remainder of this paper is structured as follows: In Section 2 we provide our baseline model. We construct optimal informational punishment and discuss its main features.

In Section 3 we generalize those insights. We derive minimal conditions on the set of available SSOs such that coordination is always optimal. We discuss the main 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. This stylized model highlights the role informational punishment plays. We consider two firms with binary types, model an SSO as simple as possible, and assume a specific market structure if firms cannot agree on an SSO. None of these restrictions is crucial for our results. In Section 3 we extend the environment to an arbitrary set of firms, types[5], and market solutions.

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 a time lag. Figure 1 sketches the model with and without informational punishment. We will see that the prospect of observing the signal disciplines firms to coordinate on an SSO in the first place.

We organize this section as follows. First, we describe the model. Second, we solve it without informational punishment. We identify parameter values inevitably leading to a standard war. Third, we introduce informational punishment to the same setting. We show that standard wars can be avoided for a (strictly) larger range of parameters.

2.1 Model

Players and Information. There are two risk-neutral firms who aim to establish a novel standard. Each firm, i, possesses binary private information $c_i \in \{1, k\}$ about its technology to implement the standard. We assume $k \geq 1$. The type is drawn according to a known, firm-specific distribution captured by p_i^0, the ex-ante probability to be type $c_i = 1$. We assume without loss that $p_1^0 \geq p_2^0$. Normalizing one of the types to 1 is without loss because only the ratio between those types matters.[6]

There are two mutually exclusive ways to determine the standard. Through the market (a standard war) or by coordination (through an SSO).

Standard War. We model the standard war as an all-pay contest. Firms compete for the right to set the standard. Winning the standard war provides the winning firm with royalties that have value normalized to 1.

The standard war is a contest with minimum investment, $r > 0$. Each firm invest $e_i \in [0, \infty)$ to convince the market that its standard is superior. Investment is costly and the marginal cost of increasing investment is c_i. We consider the simplest form of such a contest, assuming that the firm with the highest investment wins the standard war provided $\max\{e_1, e_2\} > r$. Ties are broken at random. If both firms invest less than r no standard is implemented and firms receive 0 profits. We impose the technical

[5]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.

[6]Replacing k by c_h/c_l in all expression provides an isomorphic model with types $\{c_l, c_h\}$.

assumption that $r < 1/k$ to avoid additional case distinctions.

Standard Setting Organization. An SSO eliminates the cost of the standard war. Cooperation leads to a split of the surplus from the established standard, such that firm 1 receives a share of royalties $x_1 \in [0, 1]$, and firm 2 receives the remaining royalties $x_2 = 1 - x_1$. In addition, we assume that cooperation eliminates the minimum investment r, ensuring that coordination on an SSO is the only efficient outcome from the industry's perspective.

Informational Punishment. Informational punishment consists of a signaling device, $\Sigma_i(c_i) : c_i \mapsto \Delta\{l, h\}$, for each firm. The signaling device takes type reports as inputs and maps it into a distribution of the binary outcomes l and h. In addition, the signaling device has the power to conceal any gathered information for some time. We comment on informational punishment in detail, once we construct the optimal Σ_i.

Solution Concept. We are looking for perfect Bayesian equilibria a la Fudenberg and Tirole (1988). We make the extreme assumption that any observed deviation is attributed to a low-cost firm. That is, if firm i deviates and $-i$ observes that deviation, $-i$ holds the off-path belief $p_i = 1$.[7]

2.2 Rejection without Informational Punishment

Here we consider the coordination problem when informational punishment is not available. The timing is as follows (see also Figure 1, (a)):

1. Each firm privately learns its type realization and the SSO announces the shares (x_1, x_2);
2. Firms simultaneously decide whether to accept or veto the proposal (x_1, x_2);

3a. If no firm vetoes the SSO, it is implemented and firms receive x_i;

3b. Otherwise, all veto decisions become public, and firms engage in a standard war.

We solve the game using backward induction. We start by analyzing the standard war.

Standard War. There are three possible action profiles in stage 2 that lead to a standard war: only firm 1 vetoes, only firm 2 vetoes, and both firms veto. Each of these vetoes implies an update by the firms and thus a public information structure $I = (p_1, p_2)$. Note that p_1 and p_2 might be off-path beliefs. We now describe the resulting continuation game. We describe the case $p_1 \geq p_2$. The complimentary case follows by relabeling.

[7] This assumption is innocuous. The results of Proposition 1 and 2 hold absent that assumption. No other (symmetric) off-path belief makes coordination on an SSO more likely.

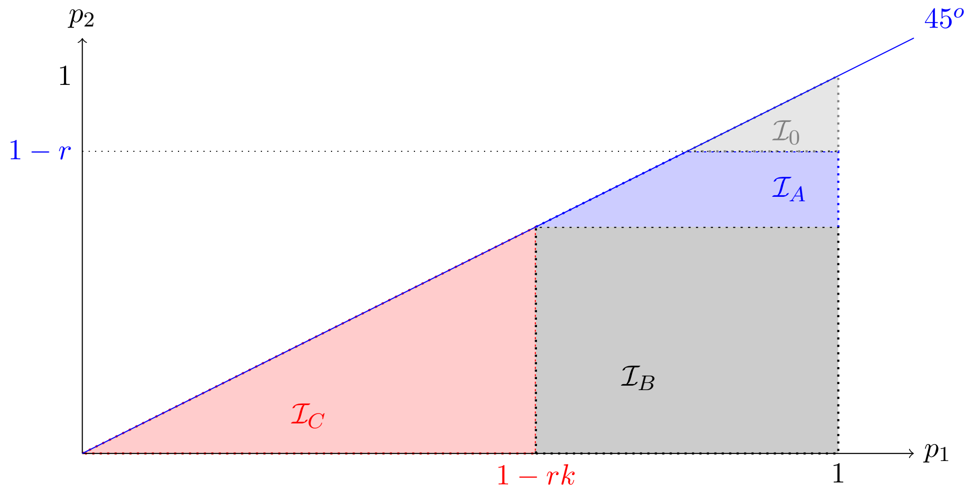


Figure 2: Partitioning the information set, given $p_1 \geq p_2$. Each partition corresponds to a type of equilibrium. See Lemma 1 for an analytical description.

Firms use the public information structure and their private information c_i to decide upon their investment. Fix firm i's strategy. Let the cumulative distribution function $F_i^{c_i}(e_i)$ denote its distribution of investment conditional on having cost c_i. The unconditional distribution $F_i(e_i) = p_i F_i^1(e_i) + (1-p_i)F_i^k(e_i)$ describes $-i$'s *expectations* about i's investment. Firm $-i$ wins the standard war if it invests more than i. To best respond to i's strategy firm $-i$ solves

$$\max_e F_i(e) - c_{-i}e.$$

There are four types of equilibria. For a given set of parameters, $\{r, k, p_1, p_2\}$, the equilibrium is unique. We describe the different types by partitioning the set of possible information structures, $\mathcal{I}$. Figure 2 illustrates the regions identified by the partition. Formally, the partition has the following subsets

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

The description of the equilibrium strategies is cumbersome as firms play mixed strategies over large intervals. We refer the reader to Appendix B for a detailed formal description. Nevertheless, the equilibrium behavior is intuitive: the equilibrium is monotonic, that is, low-cost types invest more than high-cost types. In any equilibrium the low-cost types have a common upper bound in their investment strategy. Thus, they obtain the same utility.[8]

In region $\mathcal{I}_0$, both firms have low cost with high likelihood. Competition between low-cost firms is fierce and $F_i(e)$ is relatively flat for low e. The likelihood of winning increases only little for small investments. High-cost types find it not profitable to invest r, and choose to abstain from the contest. Low-cost types expect to compete only with each other and there is full rent dissipation.

In region $\mathcal{I}_A$, the likelihood of low-cost types is smaller, but still relatively high. High-cost types still choose to abstain. However, the low-cost type of firm 1 expects to face a high-cost firm more often than firm 2 expects to do the same. The low-cost type of firm 1 has now an incentive to gamble on facing a high-cost firm. In that case its best response is to pick the minimum investment r. A low-cost firm 1 does so with some probability. As a consequence, competition is not as fierce as in region $\mathcal{I}_0$ and low-cost firms obtain positive utility.

Region $\mathcal{I}_B$ corresponds to a situation in which high-cost types are likely and the distribution is relatively asymmetric. Thus, while firm 1 expects to face a high-cost type often, firm 2 is likely to face a low-cost type. The high-cost type of firm 1 benefits from having the "reputation" of being a low-cost type with high probability and invests r. The high-cost type of firm 1 wins whenever firm 2 is the high-cost type and abstains, which happens with a probability larger than kr. This leaves the high-cost type of firm 1 with positive rents. Low-cost types earn higher rents due to their cost advantage.

Finally, in region $\mathcal{I}_C$ high-cost types are likely and the distribution is relatively symmetric. Yet firm 1 appears stronger still. In that case the high-cost firm 1 finds it beneficial to also compete with the high-cost firm 2 even if that firm does not abstain. The reason is that abstentions are less likely because firm 2 is less likely to have high cost. Investing more than r increases chances to win, but is more costly. Expected payoffs shrink for the high-cost firm 1.

From the point of view of a firm contemplating whether to accept an offer x_1, all that matters are the expected payoffs in the continuation game(s). We summarize the payoffs for the standard war in the following lemma.

Lemma 1. *Consider the game described above and take any two probability distributions $I = (p_1, p_2)$ with $p_1 \geq p_2$. Then, the expected equilibrium payoffs $V_i(c_i)$ are $V_2(k) = 0$ and*

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

[8] If firm i's maximum investment is strictly larger than that of firm $-i$, i could reduce investment and thus save cost without changing its probability of winning.

Accepting a Proposal. We now turn to the decision whether to veto a given proposal x_i. If a firm accepts the SSO it receives the (continuation) payoff x_i and the game ends. In contrast, if a firm vetoes the SSO, the standard war is triggered and we employ Lemma 1 to calculate firms' continuation payoffs. We focus on the case in which the veto of firm i is pivotal, that is, the case in which firm $-i$ is expected to accept the proposal.

Suppose firm i vetoes. Firm $-i$ concludes that firm i must be a low-cost type given the (assumed) off-path belief. Firm i is aware of firm $-i$'s updating. Firm i, in turn, cannot learn anything from its own veto and keeps the prior p^0_{-i} about firm $-i$. That is, the information structure after a veto is $I^i = (1, p^0_{-i})$. Thus, only regions $\mathcal{I}_0, \mathcal{I}_A$, and $\mathcal{I}_B$ are relevant, depending on the value of p^0_{-i}. We define firm i's continuation payoff, $v_i(c_i)$, as the expected equilibrium payoff in the continuation game after a veto, $v_i(c_i) := V_i(c_i|I = (1, p^0_{-i}))$.

We look for cases in which coordination cannot be sustained. Firm i accepts the proposal if $x_i \geq V_i(c_i)$ and rejects it otherwise. It is straightforward to obtain a condition when mutual acceptance can be guaranteed.

Lemma 2. *A standard war is inevitable if and only if* $v_1(1) + v_2(1) > 1$.

Proof. The reasoning is intuitive. Low-cost types can always mimic high-cost types and thus $v_i(1) \geq v_i(k)$. The proposal, x_i, is implementable if both players accept it. An acceptable proposal exists if and only if the low-cost types' continuation values add up to less than one. □

We conclude this part with a condition when a standard war is inevitable.

Proposition 1. *A standard war is inevitable if any of the following conditions holds*

(i) $1 - 2r - p^0_1 > p^0_2 \geq 1 - rk$,

(ii) $1 - (r + p^0_1)\frac{k}{k-1} > p^0_2$ *and* $1 - p^0_2 > rk \geq 1 - p^0_1$, *or*

(iii) $2 - p^0_1 - \frac{k}{k-1} > p^0_2$ *and* $1 - p^0_1 > rk$.

The intuition behind Proposition 1 is as follows. If the likelihood that the opponent firm has low-cost is sufficiently small, a low cost firm expects little competition. Thus, it joins an SSO only if it receives a favorable outcome. If both firms simultaneously expect to face a weak opponent, the sum of expected payoffs from a veto is larger than 1, making at least one type of one firm veto the proposal.

2.3 Informational Punishment

We now introduce informational punishment to the above model. The timing becomes as follows (see also Figure 1 panel (b)):

1. Each firm privately learns its type realization, the SSO announces the shares (x_1, x_2); and the signaling devices Σ_i are publicly announced;

2. Each firm reports to its Σ_i;
3. Firms simultaneously decide whether to accept or veto the proposal (x_1, x_2);

4a. If no firm vetoes the SSO, it is implemented and a firm receives x_i;

4b. Otherwise, all veto decisions and realization σ_i are publicly announced. Firms engage in a standard war.[9]

Different to the timing in Section 2.2, firms now have the option to report to a given signaling device, Σ_i. For now we assume that Σ_i is known and committed. That is, the signaling device takes the firm's report as input and maps it to an outcome, σ_i, according to Σ_i. Then, it truthfully reveals that outcome upon a veto. In what follows we characterize the triple $(\Sigma_1, \Sigma_2, x_1)$ that maximizes the likelihood that an SSO can be implemented.

We are going to refer to the realization l (h) as the *low* (*high*) signal. Without 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 we assume that firm 1 deviates by vetoing the SSO.

The Standard War. We guess that 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 signal realization *about* firm 1, σ_1, provides no additional information.

Suppose the signal about firm 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 p_2^0, and the realization σ_2 and updates the belief about its competitor to a posterior p_2 via Bayes' rule.

Let $\rho_i(\sigma_i)$ be the ex-ante probability that signal σ_i realizes. Consistency with the prior implies

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

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

$$\rho_2(\sigma_2 = l) = p_2^0\rho_2(\sigma_2|c_2 = 1) + (1 - p_2^0)\rho_2(\sigma_2|c_2 = k), \tag{2}$$

where $\rho_i(\sigma_i|c_i)$ is the probability that signal σ_i realizes conditional on the report c_i.

[9] 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.

The Continuation Payoffs. Fix a signaling device about firm 2, Σ_2. Its properties are commonly known and so is the lottery over posterior it induces. For each posterior Lemma 1 states the resulting payoff from the standard war. These two objects lead to a continuation payoff for a vetoing low-cost firm 1 of $v_1(\Sigma, 1) := \rho_2(\sigma_2{=}l)V_1(1|I{=}(1, p_2(l)))+$ $\rho_2(\sigma_2{=}h)V_1(1|I{=}(1, p_2(h)))$.

Acceptance is maximized if $v_1(\Sigma, 1)$ is minimized subject to consistency. Standard Bayesian persuasion arguments (see Figure 3) imply that this objective is minimized for a fully revealing high signal, that is, $p_2(h) = 0$. The low signal, in turn, is not fully revealing and induces $p_2(l) = 1 - r$. Equation (1) determines the likelihood $\rho_2(\sigma_2 = l) = p_2^0/(1 - r)$.

Why is that signal helpful? The standard war is a strategic game. The additional information firm 1 receives about firm 2's cost type, σ_2, changes its equilibrium strategy. In turn, firm 2 changes its best response. In particular, whenever the low signal arises, firm 1 expects to face the low-cost type with high probability. It responds by aggressively investing into the standard war, triggering also aggressive investments of firm 2, and rents are fully dissipated. Thus, firm 1 is worse off than under the prior. However, if the high signal realizes firm 1 is better off than under the prior. Its opponent is a high-cost type for sure. Importantly, both the high-cost type of firm 2 and the deviator, firm 1, are aware of that constellation. In turn, the high-cost type reduces its investment to at most $1/k$ and the low-cost type of firm 1 obtains a payoff of $1-1/k$. Because payoffs are non-linear in information, the loss firm 1 experiences from signal $\sigma_2 = l$ outweighs the gain it experiences from signal $\sigma_2 = h$. That is, the continuation payoff v_1 is concave in p_2 in the relevant region. From firm 1's perspective given two information structures, the expectations over continuation payoffs is less than the continuation payoff of the expected information structure. Thus, Σ_2 reduces the continuation payoff v_1.

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 $v_1(1; p_1(h))$. Moreover, $v_1(1; \Sigma)$ is the value of that line evaluated at the prior p_2^0. The dashed line in Figure 3 represents that line under the optimal signal.

Why is that signal optimal? The graphical analysis delivers the intuition. We want to minimize $v_1(1; \Sigma)$ over Σ. The smallest v_i the signal can induce is the largest convex function weakly below $v_1((1, p_2); 1)$. 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

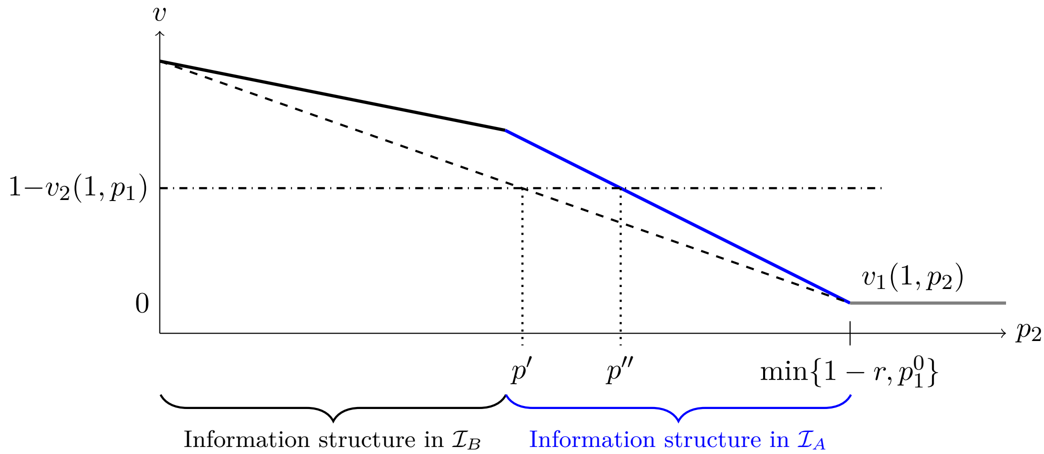


Figure 3: The value of vetoing for firm 1 given firm 2 assigns a probability p_1 to firm 1 having cost 1. The dashed line denotes the function's convex envelope. The dot-dashed depicts the residual resources after paying the minimum share to firm 2. For $k = 5$, $p_1 = 1/3$ and $r = 1/6$, it follows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

$p_2 = 1 - r$ because the veto belief $p_1 = 1$.

The result does not depend on the assumption that Σ_i has only binary output. Beyond information about the state of the world, the signaling device Σ_i can at most provide firms with action recommendations. These recommendations have to be obedient (Myerson, 1982). However, as we have stated above, the equilibrium is unique given an information structure I. Moreover, any σ_i is public. Thus, there is no room for a correlated equilibrium to improve for a given I. Since c_i is binary, a binary realization is sufficient. Finally, taking only reports of c_i as inputs is sufficient because the only information firms can provide at that point is their private information.

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. Next, 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.[10]

We conclude this part with a statement when a standard war is inevitable.

Proposition 2. *With informational punishment, a standard war is inevitable if and*

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

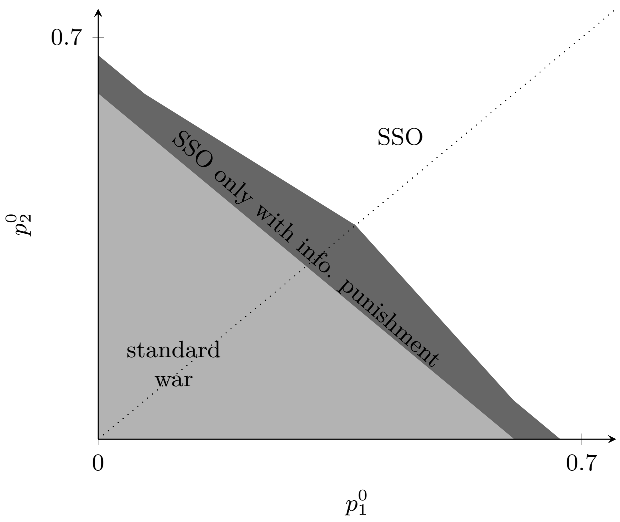


Figure 4: *Regions in which a standard war is inevitable.* In the dark shaded area a standard war can be avoided through optimal informational punishment. In the light shaded area, a standard war is inevitable with and without informational punishment. The dashed line shows the 45^0-line. Parameter values below it imply $p_1^0 > p_2^0$. The graph is drawn for $k = 4, r = 1/10$

only if

$$\frac{(1-r)(k-2)}{k-1} > p_1^0 + p_2^0.$$

Proposition 2 identifies the parameter space in which a standard war is inevitable even under informational punishment. That space is strictly smaller than that identified in Proposition 1. Figure 4 graphically illustrates the benefit of informational punishment. Informational punishment enlarges the parameter space in which coordination is possible. The main driver behind the result is how informational punishment influences firms' action choices conditional on escalation. The additional information influences the expected action choices which feeds back to the initial participation decision.

Informational punishment shifts players' beliefs about the state of the world. The shift has two effects. The first is *distributional.* The larger p_i, the more likely firm i has low cost. The second is *behavioral.* Fixing $-i$ to be a low-cost firm, the larger p_i, the fiercer the competition. Thus $-i$ invests more and, in response, so does i. In equilibrium that leads to an overproportional increase in investment making the standard war less attractive. Informational punishment exploits the second effect. Whether that exploitation is sufficient to guarantee coordination through an SSO depends on how "close" the parameters are to the region in which coordination is sustainable without informational punishment.

Informational punishment persuades firms to participate by threatening to release information that alters equilibrium play and thereby expected outcomes. However, as we see in Figure 4 informational punishment is not sufficient to guarantee participation in our simple model. We revisit that last point when we generalize our model in Section 3. If we enrich the SSO technology slightly, coordination on an SSO is always optimal. Before turning to that more general model, we discuss the main implications of informational punishment on the standard setting procedure.

2.4 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. In the remainder of this section, we discuss the implications and interpretations of our findings. We first revisit the introductory example.

The DVD standard. The model we set up above follows our interpretation of the evolution of the DVD standard. The standard war is a contest in which the two camps compete by investing into the distribution of the standard. That investment may occur downstream—through distribution of playback devices. It may also occur upstream—through distribution of recording devices. Marginal cost depend on the spillovers the respective camp has obtained while developing their standard proposal.

In our model, informational punishment is a neutral third-party that can provide an informative signal based on information provided by the firms. In the DVD case the TWG took that role. They made clear early on that their main goal was to avoid a standard war, but they were ex-ante agnostic about which side prevails. They scheduled an announcement in case the standard war was going to happen.

The threat of releasing information was sufficient to induce the formation of the DVD Consortium and the TWG had no need to make their announcement.

Alternative Interpretations

We now discuss alternative interpretations of our model. We address several business strategies common in the innovation industry and how they can be interpreted as informational punishment.

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 becomes 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 on which there is no hope for roll out. Depending on the chosen announcement, however, the signal of the outcome (roll out/vaporware) may be judged differently.

Seemingly, our model of informational punishment and vaporware are different along one dimension: In our model, the signaling device is provided by a third-party. In the vaporware case firms provide the signaling device on their own. Yet results are the same.

To see the equivalence, start with the model we set up, 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-of-type 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 off-equilibrium product announcements are considered in light of the off-path belief $p_i = 1$. Thus, these signals confirm that belief. Results are identical to the baseline model.

Leaking Documents. A second business strategy is to leak documents early on to gain advantage of the narrative. Suppose firms have the ability to leak any 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 on the information the firm leaked to the journalist and on the choice of the journalist itself. The choice of the journalist becomes the signaling device, the documents leaked are the message.

Verifiable Information. An intermediate case between informational punishment in our model and the decentralized vaporware case is one with verifiable information. Firms provide a neutral expert with information, but that expert has the option to (partially) verify these claims. The expert either finds supporting or dissenting evidence to the claims. She reports that evidence accordingly. Depending on the quality or the investment level of the third party, these investigations are more or less informative. 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.

Informational Opportunism

Here we address the role of commitment of the signal designer. Different to the baseline model, we assume the designer is a strategic player herself. She aims to avoid the standard war. However, she cannot commit ex-ante to the signaling device Σ. Dequiedt and

Martimort (2015) show that such informational opportunism can overturn the outcome derived under the commitment.

We construct a set of signaling devices, Σ_i^{EPIC}, allowing for informational opportunism. In particular, we assume that Σ_I^{EPIC} is chosen after the veto is observed, and thus *ex-post incentive compatible* for the designer. We show that the outcome is identical to our baseline model. Under informational opportunism the timing is as follows:

1. Each firm privately learns its type realization and the SSO announces the shares (x_1, x_2);
2. Each firm reports m_i to the designer;
3. Firms simultaneously decide whether to accept or veto the proposal, (x_1, x_2);

4a. If no firm vetoes the SSO, it is implemented and firms receive x_i;

4b. Otherwise, $\Sigma_i^{EPIC}(m_i)$ is chosen and publicly announced together with the veto decision and σ_i^{epic}. Firms engage in a standard war.

It is useful to identify the designer by the message she received. We call it the designer's type. We assume firms told the truth to the designer. Therefore, a *high* (*low*) device knows the non-deviating firm has high (low) cost. We construct a pooling equilibrium in which each type announces the same Σ_i^{EPIC} which is identical to Σ_i constructed above.

Consider first the *low* type. She is indifferent between any mapping that does not increase the value of vetoing for a $c_1 = 1$-deviator. That is, any signal that ensures $p_2(\sigma_i^{epic}{=}l) \geq 1 - r$ is incentive compatible. By announcing the Σ_i we constructed under full commitment, 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. Suppose she deviates from announcing Σ_i, which we constructed under full commitment. Then the vetoing firm holds the off-path belief on her being the *high* type. Thus, Σ_i satisfies the designer's incentive constraints. Thus, *allowing for informational opportunism does not alter our results.*

We are going to show in Section 3 that this result does not generalize. We provide, however, a sufficient condition when limited commitment is generally no concern.

Discussion and Limitation

Regulation. First, we step outside our model to relate our findings to regulation, one of the classic topics in industrial organizations. We briefly discuss how the option of informational punishment may affect regulation. We argue that the existence of informational punishment is relevant from the regulator's point of view, but implies an ambiguous effect on welfare.

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.

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.[11] 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. Releasing information post disagreement is beneficial if cooperation is socially desirable. In contrast, prohibiting the release is beneficial if competition is socially desirable. In the latter case it is important for regulators to recognize that the availability of a signaling 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.

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_i" exists even with informational punishment. Our model predicts a standard war without further negotiations in these cases.

In reality we seldom observe such outcomes. Even if a standard war occurs eventually, we typically observe negotiations beforehand. 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) restrict ourselves to a single take-it-or-leave-it offer.

We restrict to these SSOs 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.[12]

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

[12] Analyzing richer classes of available SSOs increases the complexity of the solution approach. In Balzer and Schneider (2019a) we address the obstacles along the way. Here we focus on the role of informational punishment.

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 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 ease of exposition. In Section 3 we drop most of these assumptions. In the following, instead, we discuss the underlying economic assumptions. We assume that vetoes become public. In fact, we only require that a firm *can* verify its veto. Indeed, vetoes have a signaling aspect. Often, a veto signals confidence and may 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.[13]

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. Results continue to hold.

3 Generalization

In this section we generalize the model from Section 2. To present our results we follow the same structure as in Section 2. We allow for an arbitrary (finite) number of firms

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

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 describe games as decision rules that map actions (i.e. type reports) into outcomes.

3.1 Model

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 $\theta_{-i} := \theta \backslash \theta_i$, 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.[14]

Throughout the paper 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 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, $\mu_\pi(\cdot|\theta) = \pi(\theta)$.

[14] 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 5. For simplicity and to maintain the intuition from the binary example in Section 2, we state Proposition 5 assuming a finite type space. However, following Kamenica and Gentzkow (2011) a similar result can be obtained for a continuous type space.

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.[15]

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 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 repli-

[15]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.

cating the market is part of this set. This assumption includes also the option of pure 'mediation' (Goltsman et al., 2009) 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 its 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.[16]

3.2 Rejection without Informational Punishment

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. Our description mirrors the channel documented in Celik and Peters (2011).

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

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

market solution.[17] 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 its 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.

3.3 Informational Punishment

If informational punishment is available, an SSO with 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 3. *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. Fixing the choices of all other firms, firm i's decision provides two information

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

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.

We want to stress two additional aspects. 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 3'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.[18]

Our second finding is that the result of Proposition 3 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 4. *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 3 and 4 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 plausible signal to influence the agent's action. Instead, the informational-punishment approach is to produce a Bayes' plausible signal that is relevant only if

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

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. Proposition 3 and 4 simplify the characterization of veto-constraint problems. They state that any optimal solution involves full participation.

For the special case that the designer can propose any game, Proposition 3 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. Moreover, characterization of the optimal mechanism is typically simpler under full participation

3.4 Interpretation and Discussion

In this part we state and discuss properties of informational punishment.

Properties of Informational Punishment

We start by a simple corollary to Proposition 3 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 (Convex Envelope)**.** The convex envelope w.r.t. to x, $vex_x(f(t,x))$, of a function f is the largest function convex in x that is (pointwise) smaller than f.

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

Definition 2 (Demanding Participation Constraints)**.** The participation constraint of type θ_i of firm i is *demanding* if the value of vetoing $v_i(\theta_i) \notin vex_I(v_i(\theta_i)$ at 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.[19]

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 $\overline{\omega}_i(I) := \max_{\theta_i} \omega_i(I;\theta_i)$.

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

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

[19] 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).

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

Informational Opportunism

As in Section 2 we now address problems in which informational punishment suffers from informational opportunism.

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 3 to 6 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, but who chooses Σ_i *after* obtaining the reports. The following assumption guarantees this.

Assumption 1 (No Fabricated Data)**.** The choice of signaling *device*, Σ, is public.

Under Assumption 1 the designer can back up any claim by providing evidence. All interested parties can see the designer's method to obtain σ.

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.*

To achieve immunity we impose two properties on the environment. Independently distributed types of 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 7. *Suppose firms' types are independently distributed and the designer types' preferences are aligned. A signaling device, Σ, is implementable by a designer that suffers from informational opportunism if and only if* no type faces unraveling pressure.

No-unraveling pressure is necessary because allowing for informational opportunism comes at a cost. In the restricted environment of Proposition 7 it is also a sufficient condition for immunity.

Corollary 3. *Suppose firms' types are independently distributed and the designer types' preferences are aligned. Then the results in Proposition 3 and 6 are immune to informational opportunism.*

As in Section 2 it is useful to identify the designer by her *type*, that is, by the information she holds *after* having collected the firms' private information. 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. 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.

Firms that do not face unraveling pressure, 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 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, then Σ is implementable even by a designer that suffers from 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 7 applies.

Corollary 4. *Suppose firms' types are independently distributed and the designer types' 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 Punishment. We now turn to a weak form of informational punishment. The designer can commit to a signal Σ prior to firms' reporting, but can choose to conceal its realization.

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.

Under weak informational opportunism all our results continue to hold if the designer types' preferences are aligned and types are independently distributed.

Corollary 5. *Suppose firms' types are independently distributed and the designer types' preferences are aligned. Proposition 3 to 6 are immune to weak informational opportunism.*

Moreover, if the designer suffers from weak informational opportunism only, the firms' perception of the designer's objective is irrelevant. The results from Proposition 3 to 6 continue to hold regardless of that perception. It remains important, however, that the preferences *between* designer types are aligned. Informational punishment is robust against firms' ambiguity with respect to the designer's objective even if the designer suffers from weak informational opportunism.

Corollary 6. *Suppose firms' types are independently distributed and the designer types' preferences are aligned. Proposition 3 to 6 are immune to weak informational opportunism even when ambiguous about the designer's objective function.*

Corollary 5 and 6 are a corollary to Proposition 7. If the designer's preferences are aligned between types, Σ has a 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 the SSO. 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 proposed SSO 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. If firms are able to observe the other's veto decision, 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, in a hypothetical equilibrium in which information is ignored, the deviator has strict incentives to learn the information if it is available.

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 action choices. Moreover, since signals do not realize on the equilibrium path, the signaling device serves as a pure threat and privacy considerations play no role.

5 Conclusion

We consider an SSO seeking to determine a standard in an industry. 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 an SSO. We show that the threat of the signal's realization relaxes firms' participation constraints.

Our model contributes to the discussion whether "it is 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" once firms cannot coordinate. Indeed, in the standard setting procedure for cellular network technologies such as xG-networks participation in the SSOs has become less of an issue. The participation decision has shifted from SSOs to forming patent pools. Our model applies.

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. Vetoes and Bayesian games as outside options are present in many areas of industrial organization and law and economics. 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 on a borrower 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.

Appendix

A Proofs

A.1 Proof of Lemma 1

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

A.2 Proof of Proposition 1

Proof. Recall that our off-path belief restriction implies a belief $p_i = 1$ on the deviator i. We take the cases in turn.

Case 1: Assume $1 - 2r - p_1^0 > p_2^0 \geq 1 - rk$. Lemma 1 and $r \leq 1/k$ implies a post-deviation information structure in region $\mathcal{I}_A$ (up to relabeling the firms). By Lemma 2 a standard war is inevitable if

$$v_1(1) + v_2(1) = 2 - 2r - p_1^0 - p_2^0 > 1 \Leftrightarrow p_2^0 < 1 - 2r - p_1^0.$$

Case 2: Assume $1 - (r + p_1^0)\frac{k}{k-1} > p_2^0$ **and** $1 - p_2^0 > rk \geq 1 - p_1^0$. Lemma 1 implies a post-deviation information structure in region $\mathcal{I}_A$ (plus relabeling) if firm 2 deviates and in region $\mathcal{I}_B$ if firm 1 deviates. By Lemma 2 a standard war is inevitable if

$$v_1(1) + v_2(1) = 1 - r - p_1^0 + (1 - p_2^0)\frac{k-1}{k} > 1 \Leftrightarrow p_2^0 < 1 - (r + p_1^0)\frac{k}{k-1}.$$

Case 3: Assume $2 - p_1^0 - \frac{k}{k-1} > p_2^0$ **and** $1 - p_1^0 > rk$. Lemma 1 implies a post-deviation information structure in region $\mathcal{I}_B$ (up to relabeling the firms). By Lemma 2 a standard war is inevitable if

$$v_1(1) + v_2(1) = (2 - p_1^0 - p_2^0)\frac{k-1}{k} > 1 \Leftrightarrow p_2^0 < 2 - p_1^0 - \frac{k}{k-1}.$$ □

A.3 Proof of Proposition 2

Proof. Suppose firm i rejects the mechanism. Then, $p_i = 1$. Moreover, the optimal signal implies that $p_{-i}(h) = 1$ and $p_{-i} = 1 - r$. Thus, $\rho_{-i}(l) = p_{-i}^0/(1 - r)$ and $v_i(\Sigma^*, 1) = (1 - \rho_{-i}(l))\frac{(k-1)}{k} = (1 - r - p_{-i}^0)(k-1)/(k(1-r))$. Thus, $\sum_i v_i(\Sigma^*, 1) > 1$ if and only if

$$(2(1 - r) - p_1^0 - p_2^0)\frac{(k-1)}{k(1-r)} > 1 \Leftrightarrow \frac{(1-r)(k-2)}{k-1} > p_1^0 + p_2^0.$$ □

A.4 Proof of Proposition 3

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 firm i 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. $\square$

A.5 Proof of Proposition 4

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 3. Suppose this equilibrium satisfies refinement $(\star)'$.

We show that the full-participation equilibrium constructed in the proof of Proposition 3, (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. □

A.6 Proof of Proposition 5

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. □

A.7 Proof of Proposition 6

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 3. The only difference is that the signaling function also replicates the potential signal-by-mechanism-choice behavior of the principal, captured by Σ_0. $\square$

A.8 Proof of Proposition 7

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. $\square$

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.

B.1 Equilibrium Strategies and Expected Payoffs in the All-Pay Auction

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 3. 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

$$
\begin{aligned}
V_i(c_l) &= \Delta_2(k-1),\\
V_1(k) &= (\Delta_2 - r)(k-1),\\
V_2(k) &= 0.
\end{aligned}
$$

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

$$
\begin{aligned}
V_i(c_l) &= = \Delta_2(k-1),\\
V_1(c_h) &= (\Delta_2 - \Delta_1)(k-1),\\
V_2(c_h) &= 0.
\end{aligned}
$$

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.[20]

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 e_i that satisfies:

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

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

[20]See below for the respective argument.

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

$$
\begin{aligned}
V_1(k) = (1 - p_2)\frac{(k-1)(1-p_2) + rk}{k(1-p_2)} - rk &= \\
\frac{(k-1)(1-p_2) + rk - r(k)^2}{k} &= \\
\frac{(k-1)(1-p_2) - rk(k-1)}{k} &= \\
(k-1)(\Delta_2 - r)
\end{aligned}
$$

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 $e \in (r, \Delta_1)$ yields utility

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

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.

□

B.2 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 4 (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 $0 \cup (r, \overline{e}]$ for some $\overline{e}$. Firms don not have a mass point on $(r, \overline{e}]$. Moreover, $\overline{e} \leq 1/c_i$ where the last inequality follows from (v).

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

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

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 $Pr(e_i > e_{-i}|I) = p_{-i}F_{-i,1}(e_i) + (1-p_{-i})F_{-i,k}(e_i)$. By property (iv) of Lemma 4 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 4 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 $(r, \overline{e}]$ for some $\overline{e} < 1$. 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.

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