# Persuading to Participate: Coordination on a Standard*

Benjamin Balzer†　　Johannes Schneider‡

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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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†University of Technology Sydney, benjamin.balzer@uts.edu.au

‡Universidad Carlos 3 de Madrid, jschneid@eco.uc3m.es

# 1 Introduction

The road to the standard for high-resolution home-video 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.[1]

*Why did both camps at first refuse to cooperate?* One explanation is that they had private information about their prospects in the standard war. Both may have been optimistic that their product is likely to prevail in the market. Thus, 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. When evaluating their strategic options both parties put little weight on the event of facing a strong competitor. Mutual optimism implies that each party expects a favorable outcome. Yet, an SSO can at most grant it one of them. In turn, 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 aspects are important. First, the announcement was credible. As Toshiba executive Koji Hase puts it, TWG chairman 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.*'[2] Second, the announcement implied that the TWG was going to release the outcome of their evaluation at a later date.

The TWG committed to release information about the technologies, if parties could not find a solution on their own. That commitment overcame the coordination failure of mutual optimism. The TWG was not interfering with the market mechanism itself. Instead, it influenced the expected information structure. Moreover, it did so by *announcing* to produce a signal

[1]For more on the development of the DVD standard see Taylor, Johnson, and Crawford (2006) or an article by Stewart Wolpin on the history of the DVD that originally appeared in *DVD etc* (2007), now online available at `http://stewartwolpin.com/2015/09/the-history-of-dvd/`. For the view of industry observers at the verge of the standard war see e.g. `https://tinyurl.com/y4l5yjjx`.

[2]Quote taken from the Wolpin article.

rather than producing the actual signal.[3]

Most industries operating in two-sided markets consolidate to a *de-facto standard* eventually. A standard is a platform that 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. Firms 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.[4]

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 firms agree on forming an 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. It has two realizations per firm. We refer to it as *informational punishment.*

Informational punishment has a variety of desirable features: (i) it respects firms privacy, that is, the probability that the signal realization becomes public is zero in equilibrium; (ii) it does not interfere with firms' incentives inside the SSO; (iii) a decentralized implementation is possible, that is, firms can design informational punishments themselves; and (iv) the actual punishment does not require enforcement by a third party. It results from the complying firms' competitive market behavior.

We proceed in two steps. First, provide a stylized mode of the standard-setting process that is sufficient to deliver the main intuition behind informational punishment (Proposition 1 and 2). Second, we show that the stylized example can be extended in ample ways with the results remaining in place. We derive a condition when informational punishment improves (Proposition 4) and two conditions on an SSO such that full participation is optimal if informational punishment is available (Proposition 5).

Our *stylized model* is inspired by the DVD case. Two firms are on the verge of a standard war. A third party collects information from firms and promises to release (parts of) the information if coordination fails. We construct the optimal information-revelation device and show how it facilitates coordination on a standard.

Informational punishment is implementable (i) through the SSO itself, or (ii) by each firm individually. We discuss several business strategies that implement informational punishment: product pre-announcements, information leakage, and the provision of beta versions. Finally, we address the role of commitment of the signal provider. We show that incentives for opportunistic behavior are of no concern.

[3]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.

[4]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 Blu-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 can be observed in the Blu-Ray case.

The main motivation of this paper comes from the formation of SSOs. However, our findings apply to any setting in which coordination happens in the shadow of a market solution. Examples include environmental agreements, coordination between legislators, strikes, litigation, and R&D alliances.

**Results.** Our analysis shows that the announcement to produce a signal about one firm's cost structure can persuade other firms to join an SSO. The announcement relaxes participation constraints and thereby increases the set of implementable SSOs.

Informational punishment works because a signal realization about firm $i$ has two effects. The first effect is direct and distributional. It changes the other firms' perception about firm $i$'s cost structure. The second effect is indirect and behavioral. A firm's continuation strategy is a function of the information set of the firm. Obtaining more information alters the firm's continuation strategy. Via equilibrium reasoning the firm's change in behavior alters the behavior of other firms in the market.

Bayesian updating implies that the distributional effect averages to the prior distribution. The same does not hold for expected payoffs. The reason is the behavioral effect. Firms expect to adjust their behavior after each realization. Their continuation payoffs depend on the adjusted strategy profile. Generically, expected payoffs are thus non-linear in the information structure. Hence, expected payoffs before the signal's realization are not equivalent to expected payoffs if there is no signal at all.

Informational punishment exploits the behavioral channel. It decreases firms' outside options and thereby relaxes participation constraints. Under informational punishment, firms commit to release parts of their private information in case another firm vetoes the SSO. Releasing information influences the action choices of all firms in the market—those participating and those vetoing. The threat of information release persuades firms to participate in the SSO.

Informational punishment has a set of additional attractive features. It separates the signaling effect of a veto from firms' participation decisions. It has no direct effect on either the (expected) outcome of the SSO or the incentive constraints. The reason is that informational punishment operates off the equilibrium path. Informational punishment is credible under perfect Bayesian equilibrium and survives common refinements. Informational punishment enlarges the set of implementable SSOs. Yet, it does not rely on the ability to enforce actions, or on non-credible threats.

**Related Literature.** In line with Simcoe (2012) we assume that standard setting is a process in which industry consensus overcomes 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 organizations 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.[5]

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 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 outcomes. 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' best respond 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 in these models 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.

[5] 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.

The fact that full participation need not be optimal is documented in Celik and Peters (2011). We provide a simple device that erases the benefits from on-path rejection they describe. 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.

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

Balzer and Schneider (2019b) 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 either Balzer and Schneider (2019a,b): Participation constraints are *non*-demanding in the sense of Definition 2 given on page 23 in this paper.[6]

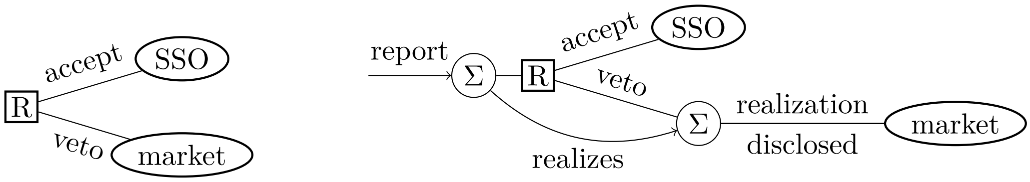
**Roadmap.** The remainder of this paper is structured as follows: In Section 2 we provide a stylized model of standard setting. We construct optimal informational punishment and discuss its main features. In Section 3 we discuss features of SSOs we abstracted from in the Section 2. Our main results are robust to adding these features. We derive minimal institutional requirements on the space of available SSOs such that coordination is *always* optimal. Section 4 concludes. All proofs not provided in the main text are in the appendix.

## 2 Coordinating on a Standard

In this section we present a stylized model of standard setting. Our model highlights the role of informational punishment. To focus on the main channel we abstract from many real-world aspects and focus on two firms an binary types. Our results do not depend on the simplifications. See Section 3 and Appendix B.3 for a general discussion. Figure 1 sketches the model with and without informational punishment. We show that the prospect of observing the signal disciplines firms to coordinate on an SSO.

We organize this section as follows. First, we describe the stylized model. Second, we solve it without informational punishment. We identify parameter values such that a standard war is inevitable. Third, we introduce informational punishment to the same setting. We show that

[6]In addition to our own work see also Zheng (2019) who also leaves no room for informational punishment. All these papers share that they model the outside option as an application of Szech (2011) and Siegel (2014). Moreover, the literature on information sharing in Cournot oligopolies (see e.g. Fried, 1984; Li, 1985; Okuno-Fujiwara, Postlewaite, and Suzumura, 1990) find that information sharing is beneficial even among competitors. The reason is precisely convexity of profit functions in beliefs. In such industries coordination on the optimal SSO is possible also absent informational punishment because participation constraints are not demanding.




(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, $\Sigma$, to which firms report *before* (R). The signal realization becomes public only *after* (R).

standard wars can be avoided for a (strictly) larger range of parameters. Finally, we discuss several real-world interpretations of informational punishment.

## 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.[7] 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. Only the ratio between types matters.[8]

There are two—mutually exclusive—ways to determine the standard. Through the market (a standard war) or through 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 an expected payoff 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 assumption that $r < 1/k$ to avoid additional case distinctions.

**Standard Setting Organization.** An SSO eliminates the cost of the standard war and thus generates surplus. We model the SSO as simple as possible. We assume that cooperation leads to a split of the surplus from the established standard, such that firm 1 receives a share of surplus $x_1 \in [0, 1]$, and firm 2 receives the remaining surplus $x_2 = 1 - x_1$. In addition, we

[7] Alternatively, we can think of these two firms of having a (not yet fully) developed format. Private information is then about the quality of the format, that is, the cost of fully developing it and bringing it to the market.

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

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 them into a distribution over 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 $\Sigma_i$.

**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 $p_i = 1$.[9]

## 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 and focus on the case $p_1 \geq p_2$. The complimentary case follows by relabeling.

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

[9] 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.

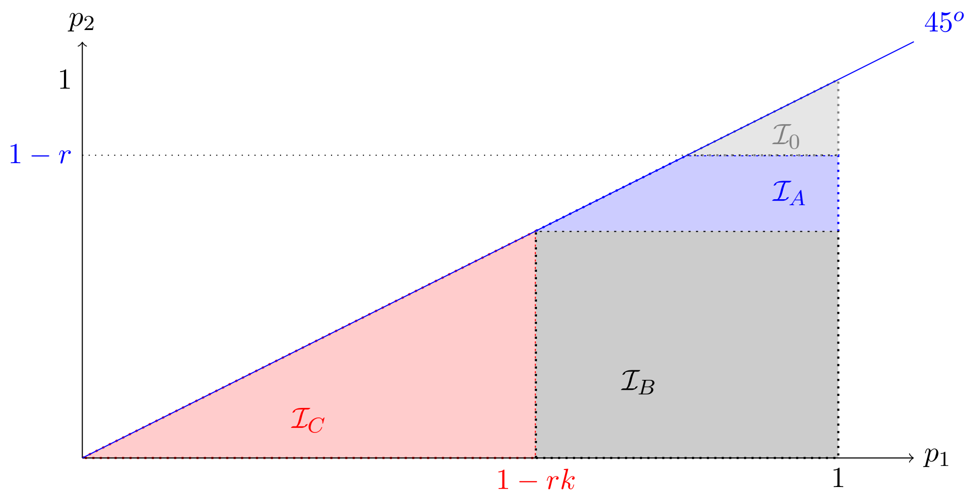



Figure 2: Partitioning the information set, given $p_1 \geq p_2$. Each partition corresponds to a type of equilibrium. See Lemma 1 for an analytical description.

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

In general, the description of the equilibrium strategies is cumbersome as firms play mixed strategies over large intervals. We refer the reader to Appendix C 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.[10]

In the analysis that follows our focus is on information structures of the form $I = (1, p_2)$, that is, the right boundary of the set depicted in Figure 2. We now discuss the intuition behind the three regions $\mathcal{I}_0, \mathcal{I}_A, \mathcal{I}_B$ assuming an information structure $I = (1, p_2)$. Our statement about equilibrium payoffs, Lemma 1, however take all possible information structures into account.

In region $\mathcal{I}_0$, firm 2 has 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 of firm 2 find it not profitable to invest $r$, and choose to abstain from the contest. Low-cost types expect to compete only with another low-cost type. Full rent dissipation follows.

In region $\mathcal{I}_A$ and $\mathcal{I}_B$, the likelihood that firm 2 has low-cost is intermediate. The low-cost type of firm 1 expects to face a high-cost firm 2 more often than in $\mathcal{I}_0$. Therefore, firm 1 has an incentive to gamble on facing a high-cost firm 2. Its best response is to pick the minimum investment $r$ with some probability. As a consequence, competition is not as fierce as in region $\mathcal{I}_0$ and low-cost firms obtain positive utility.

[10]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.

The difference between regions $\mathcal{I}_A$ and $\mathcal{I}_B$ is in the behavior of firm 2, type $k$. While a high-cost firm 2 chooses to abstain from competition in region $\mathcal{I}_A$, it chooses to participate in the standard war in region $\mathcal{I}_B$. The reason for participation is that a low-cost firm 1 chooses the minimum investment with sufficiently high probability if her competitor is likely to have high cost.

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. The proof of it builds on Siegel (2014).

**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*

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

**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. However, firm $i$ 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 say a standard war is *inevitable* whenever it is impossible to make an offer $x_i$ that all firms and types accept with probability 1. 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.[11]

**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*

[11] An analog to Lemma 2 can be found e.g. in Compte and Jehiel (2009), Balzer and Schneider (2019b), and Zheng (2019).

*(iii)* $2 - p_1^0 - \frac{k}{k-1} > p_2^0$ *and* $1 - p_1^0 > rk$.

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 $\Sigma_i$ are publicly announced;
2. Each firm reports to its $\Sigma_i$;
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 $\sigma_i$ are publicly announced. Firms engage in a standard war.[12]

Different to the timing in Section 2.2, firms now have the option to report to a given signaling device, $\Sigma_i$. For now, we assume that $\Sigma_i$ is known and committed. That is, the signaling device takes the firm's report as input and maps it to an outcome, $\sigma_i$, according to $\Sigma_i$. 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 $\Sigma_i$ 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, $\sigma_1$, provides no additional information.

Suppose the signal about firm 2 has realized to $\sigma_2$. 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 $\Sigma_2$, the prior $p_2^0$, and the realization $\sigma_2$ and updates the belief about its competitor to a posterior $p_2$ via Bayes' rule.

[12] In principle, $\Sigma_i$ 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.

Let $\rho_i(\sigma_i)$ be the ex-ante probability that signal $\sigma_i$ 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 $\sigma_i$ realizes conditional on the report $c_i$.

**The Continuation Payoffs.** Fix a signaling device about firm 2, $\Sigma_2$. 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, $\sigma_2$, 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, $\Sigma_2$ 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 $\Sigma$. The smallest $v_i$ the signal can induce is the largest convex function

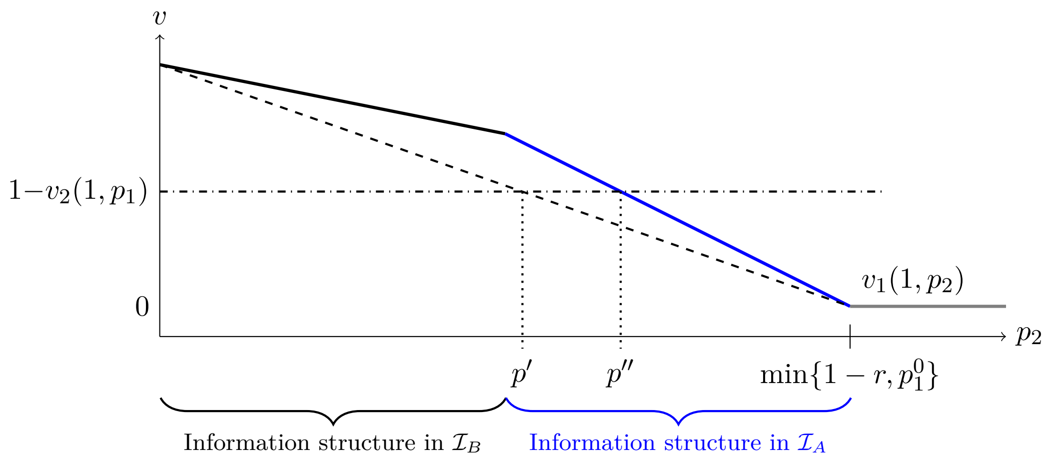



Figure 3: The value of vetoing for firm 1 given firm 2 assigns a probability $p_1$ to firm 1 having cost 1. The dashed line denotes the function's convex envelope. The dot-dashed depicts the residual resources after paying the minimum share to firm 2. For $k = 5$, $p_1 = 1/3$ and $r = 1/6$, it follows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

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

The result does not depend on the assumption that $\Sigma_i$ has only binary output. Beyond information about the state of the world, the signaling device $\Sigma_i$ 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 $\sigma_i$ 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.[13]

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

**Proposition 2.** *Suppose both firms have low cost. With informational punishment, a standard*

[13] 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.

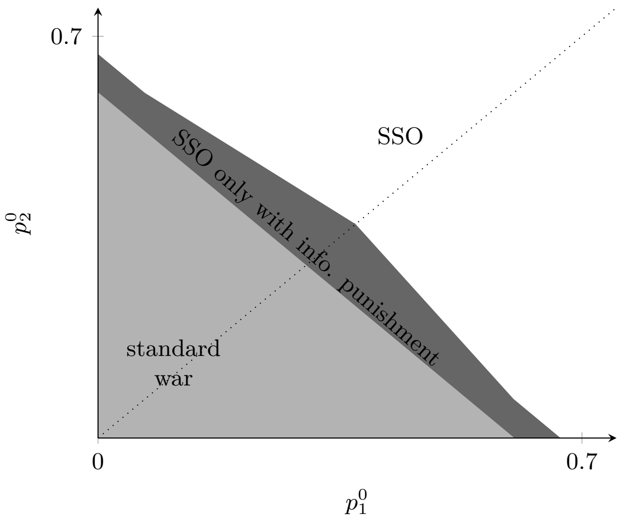



Figure 4: *Regions in which a standard war is inevitable.* In the dark shaded area a standard war can be avoided through optimal informational punishment. In the light shaded area, a standard war is inevitable with and without informational punishment. The dashed line shows the $45^0$-line. Parameter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

*war is inevitable if and 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 over-proportional increase in investment making the standard war less attractive. Informational punishment exploits the second effect. Whether that exploitation 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 Appendix B. 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

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.[14] 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. It is less obvious that the TWG also had the commitment power we assume in the model above. In fact there may have been room for informational opportunism. We address that point after our discussion of alternative implementations of informational punishment.

### Informational Punishment Through the SSO

An alternative way to interpret our model is to assume that the SSO itself includes informational punishment. Provided that a neutral third party governs the SSO, such an interpretation is without loss. That is, if the TWG had simultaneously set up the SSO *and* the informational punishment mechanism, results would be identical. As in the above interpretation, commitment power seems crucial at first sight. However, we show below that informational opportunism is no concern. For a general discussion on non-neutral SSOs see also appendix B.4.

### Decentralized Informational Punishment

We now turn to the scope of informational punishment provided by the firms themselves. We address several business strategies common in the innovation industry and how they can be interpreted as means of informational punishment.

[14] See also the articles mentioned in Footnote 1.

**Vaporware.** Vaporware describes products that are pre-announced but then never produced. Announcing products before production has even begun is a common business strategy in standard wars (Shapiro and Varian, 1998, chp. 9). Using these product announcements to influence strategic behavior of rivaling firms is well documented. Here we argue that product announcement can serve as informational punishment.[15]

Consider our baseline model without informational punishment. In addition, assume that the firm announces a product that is not yet fully developed prior to its decision whether to join the SSO. The likelihood of the product's realization is correlated with the underlying cost function. In case an SSO decides on the standard and firms coordinate, the announcement has no strategic value. However, if the SSO is rejected, the market observes whether the product is actually developed or has become vaporware. Firms update beliefs and choose their strategies in the market.

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 a product on which it has no intention to work on. Depending on the announcement, the outcome (roll out/vaporware) may be interpreted differently. Thus, the announcement determines the precision of the signal.

The main difference between product announcements and the informational-punishment mechanism outlined above is that here firms choose the signal precision themselves and do not delegate it to a third party.

Now suppose the following announcement strategy. Both the high-cost firm and the low-cost firm announce a product that is straightforward to develop for a low-cost firm, but development may fail if the firm has high cost. Then, 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. Calibrating the difficulty for high-cost firms correctly replicates the optimal signal constructed above.

Firms completely control the precision of the signal when making a product announcement. We show that they have no incentive to deviate through a different announcement strategy. We start by announcements that fully reveal the type. For a low-cost deviator a proof-of-type is irrelevant as the non-deviating firm holds that belief already for any potential deviation. A high-cost deviator never profits from proving its high cost. All non-fully-revealing off-equilibrium product announcements are considered in light of the off-path belief $p_i = 1$. Thus, any difference in the announcement strategy confirms that belief. Results are identical to the baseline model.

**Leaking Documents.** An important aspect in standard wars is to gain advantage of the narrative of the standard war.[16] While releases by the firms may not have too much of an impact, their evaluation by the business press has the potential to affect the narrative (see Bushee et al., 2010, for empirical work on the role of the press).

[15] Among others Dranove and Gandal (2003) provide evidence for the use of vaporware in standard setting. Bayus, Jain, and Rao (2001) analyze the presents of vaporware in innovative markets in general. Theoretical arguments are provided by Farrell and Saloner (1986) and Besen and Farrell (1994).

[16] "It's not enough to have the best product; you have to convince consumers that you will win", Shapiro and Varian (1998, chp. 9)

To influence press coverage firms can strategically leak information to the press. If the information is evaluated positively, this may help to gain advantage of the narrative in the standard war and provide a coordination device for yet undecided consumers. If the information is evaluated negatively, the opposite may be the case.

In addition, assume that (i) journalists fact check the information and bundle it with their own investigation, and that (ii) the information is most valuable to journalists in case the firms cannot coordinate on a standard. Then the press has an incentive to publish its evaluation of the information only after coordination on a standard failed.

Under these assumption information leakage works precisely as the product pre-announcements. All firms leak similar information to the press. While the press cannot find contradictory evidence if the firm has low cost, it sometimes finds contradictory evidence if the firm has high cost. The optimal signal is replicated. Similar to the vaporware discussion, firms have no incentive to leak different information to the press.

**Beta Versions.** Another strategy to influence the information in the market is to provide beta versions of the intended product range. While yet incomplete, beta versions provide information about the expected quality of the final product and thereby influence strategies of the rivaling firms. The main strategic difference to information leakage and product announcements is that beta versions may contain hard evidence about the firm's cost structure. Indeed, by analyzing a rival's beta version, a firm can partially verify that rival's technology. Other than that, beta versions work the same way as the other two strategies.

Results are identical to those in our baseline model. All firms claim low cost with their beta version. If the beta version contains severe bugs (the $h$-signal) the market updates negatively, otherwise it updates positively (the $l$-signal). As in the previous two cases, the firm has no incentive to intentionally provide bugs to signal high-cost.

**Informational Opportunism**

Here 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 $\Sigma$. Dequiedt and Martimort (2015) show that such informational opportunism can overturn the outcome derived under the commitment.[17]

We construct a set of signaling devices, $\Sigma_i^{EPIC}$, allowing for informational opportunism. In particular, we assume that $\Sigma_I^{EPIC}$ 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 $x_i$;

[17] The TWGs press releases (see Taylor, Johnson, and Crawford (2006) for a discussion) arguably suggest that the TWG was indeed a strategic designer and therefore may have suffered from informational opportunism.

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

**Proposition 3.** *Informational Punishment is immune to informational opportunism, i.e. the optimal signals, $\Sigma_i^{EPIC}$ and $\Sigma_i$, in the two scenarios coincide, $\Sigma^{EPIC} = \Sigma_i$.*

*Proof.* The proof is constructive.

It is useful to identify the designer by the message she received. We call it the designer's type. For now, 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 $\Sigma_i^{EPIC}$ which is identical to $\Sigma_i$ constructed above.

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

### Discussion and Limitation

**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 Blu-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.[18]

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 question immediately arises from this observation: How do the benefits of informational punishment generalize to richer SSOs? The answer to this question is provided in Section 3. We show that informational punishment (i) guarantees participation in an SSO (even if the SSO cannot guarantee an agreement on a standard), and (ii) increases the set of implementable SSOs if the space of SSOs satisfies mild minimal restrictions.

[18] Analyzing richer classes of available SSOs increases the complexity of the solution approach. Balzer and Schneider (2019a) address the obstacles along the way.

**Underlying Model Assumptions.** The simplifying technical assumptions we made in this section are for ease of exposition only. In Appendix B we drop most of these assumptions. In the following, instead, we discuss the underlying economic assumptions. We assume that vetoes become public. Yet, 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 standard (partially) replaces some 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.[19]

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.

## 3 Standard-Setting Organizations

The stylized model of Section 2 provides a simplistic view on standard setting. First, we assume two types and two firms only. Second, we abstract from features of real-world SSOs by viewing it as a black box that describes how expected surplus from the standard is distributed. In reality, however, SSOs are diverse and complicated decision-making bodies (see Baron and Spulber, 2018, for an overview) that consist of heterogeneous firms and may not require consent.

Here we discuss why incorporating a more complicated environment and a realistic institutional framework for SSOs does not change the heart of our analysis. Thereafter, we provide a condition that determines when informational punishment is useful and a sufficient condition that determines when informational punishment can guarantee full participation in the optimal SSO.

In Appendix B we present the formal counterpart to our discussion. We develop a general yet abstract model using the techniques and language of mechanism design to model SSOs. We drop most of our technical assumptions and allow for an arbitrary set of SSO proposals. Our main result—informational punishment aides coordination on an SSO—continuous to hold.

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

## 3.1 The Institutional Framework of SSOs

### Frictions within SSOs

Assuming that firms face no frictions when agreeing on how to share the surplus generated by forgoing a standard war may be overly simplistic and even problematic given antitrust laws. In reality, firms may form an SSO *before* negotiating over which patents to include in a standard and over which terms of cross-licensing apply. SSOs may consist of heterogeneous firms. Some firms provide the technology and others adopt it. In addition, it may be the case that *despite* the formation of an SSO a standard war occurs eventually. An example of such a case is the standard war between HD-DVD and Blu-ray, the technology proposals succeeding the DVD standard.

None of those frictions affects the results from Section 2. The reason is that informational punishment *discourages* firms to veto rather than promising them higher payoffs from participating. If a firm provides informational punishment, it discourages other firms from choosing the market mechanism. Thus, informational punishment works independent of the design of the SSO.

To emphasize this point consider a specific setting. Assume the SSO provides a forum that structures negations between firms with (partially) misaligned incentives. For example, in Farrell and Simcoe (2012) two firms are privately informed about the quality of their technology. A firm receives a payoff from sponsoring the technology that becomes the standard. At the same time both firms' payoffs increase in the quality of the standard's technology. In such a setting, the SSO chooses the technology via (costly) bilateral negotiations. Selection of the standard is modeled as a war of attrition with costly delays. In equilibrium, the firm with the best technology wins that negotiation. Translated to our model, participating in the SSO leads to a payoff that is decreasing in the firm's cost $\theta_i$, captured by a decreasing function $x_i(\theta_i)$. As in the model of Section 2 (Lemma 2), a standard war is inevitable for two low-cost firms if $v_1(1) + v_2(1) \geq x_1(1) + x_2(1)$.

Farrell and Simcoe (2012) characterize the scope for random interventions. While ending (too long-lasting) wars of attrition, random interventions increase firms' total profits. The intervention comes at the cost of screening and, in turn, lowers the profits of low-cost firms. Thus, a low-cost firm may prefer to separate via the market game instead of joining an SSO. The reason is that within the SSO it may be pooled with a high-cost firm through random interventions. Informational punishment eases this firm's participation constraint and makes more interventions implementable.

### Many firms

Standards in the computer industry or the cell-phone industry are perhaps subject to larger technological complexity than the standard for discs, (at first) only designed for video playback. As a consequence, the variety of participants may be greater. However, even in the introductory example of the DVD case several firms had organized themselves into the two industry consortia. Despite such organization each firm may still have its own agenda. Like forming an all-inclusive SSO, forming a consortium—an SSO that sponsors a particular standard against the alternatives outside the SSO—is beneficial. It increases the surplus of the participating firms by allowing them to coordinate their strategies.[20]

Within our model we can treat outsiders as exogenously given. Once formed, the consortium competes with the remaining firms/consortia in a second stage. Yet, an consortium provides each participating firm with an expected surplus $x_i(\theta_i)$ that depends on its private information. That expected surplus has to be larger than a firm's value of vetoing $v_i(\theta_i, I^0)$, which may be the (expected) payoff from joining the *competing* consortium. In particular, if key players are expected to not participate, $x_i(\theta_i)$ decreases and thus other firms may want to stay outside the consortium too, leading to complete breakdown of the consortium. Informational punishment of firm $i$ can facilitate participation of firm $j$ precisely as in Section 2. If it does, and firm $i$ finds it beneficial to make firm $j$ participate. There is room for informational punishment.

A second aspect absent in the two-firm model occurs if we design an SSO which all firms are supposed to join, but a single veto allows for coordinated actions by the remaining firms. If firms can hand over authority to the SSO, such a scenario provides an additional instrument of punishment to the SSO. If a firm that is supposed to participate deviates, the SSO dictates the complying firms to choose the market action that minimizes the deviator's payoff. Depending on the SSO's commitment power the scope of such "punishing the deviator" strategies varies. If the SSO has full authority and commitment power, it can promise to punish a deviator even at the cost of the participating firms. If, however, the commitment power of the SSO is limited, the punishment is limited to making (interim) optimal choices.

Informational punishment is orthogonal to the SSO's authority and commitment power. It punishes a potential deviator through information about the complying firms. It does not condition on the SSO itself nor on the commitment options of the outside *competitors*. Instead, it requires only that firms can conceal some information and credibly commit to release information in case participation turns out to be different than expected.

In any of the above extensions an industry consists of $N$ firms. Depending on the context, an SSO may only target $N' \leq N$ of them. A targeted firm's continuation payoff from accepting an SSO depends on the bargaining protocol or the voting procedure within the SSO and also on what happens after an SSO came to a decision. In general, the firm's interaction within an SSO could be a complicated dynamic process. For example, SSOs might not adopt standards by unanimous consent. That is, even though all $N'$ targeted firms initially agreed to join the SSO to set up a standard, only a subset of them eventually agree on one.

Nevertheless, our model remains valid. Equilibrium behavior conditional on joining an SSO implies a mapping from firms' private information to (i) the $N'$ firms' joint payoffs and to (ii) a distribution of these payoffs among the $N'$ firms.[21] A firm only joins an SSO if its continuation payoff from that action, $x_i(\theta_i)$, is larger than the value from not joining the SSO.

[20] An example of such consortium formation is the Blu-ray Disc Foundation/HD-DVD Promotion Group in 2004.

[21] This could be, for example, the continuation payoffs from teaming up, as in the formation of the MMCD/SD camps where $N' = 2$.

## 3.2 Informational Punishment and SSOs

In this part we summarize the findings from our general model in Appendix B. We derive two conditions. First, we determine when informational punishment is *necessary* to implement a certain outcome. Second, we determine when informational punishment is *sufficient* to guarantee full participation at the optimum.

To provide the first condition, we fix the SSO's implementation goal and characterize the environment that makes informational punishment necessary for implementation. We also comment on how to asses sufficiency in this context.

To derive the second condition, we provide a minimal condition on the set of available SSO mechanisms such that informational punishment guarantees full participation. In Appendix B.2 we demonstrate that informational punishment may also be necessary even if the designer has full flexibility to design the SSO.

**When is informational punishment useful?** Here we discuss when informational punishment is necessary for implementation. We fix an SSO and the associated expected outcome $x_i(\theta_i)$ to each participating firm $i$, type $\theta_i$. We are interested in a case in which a specific firm's type $\theta_i$ rejects the proposed SSO absent informational punishment. The question we want to answer is: can we find an informational-punishment mechanism that, all else equals, persuades $\theta_i$ to participate?

The described setting includes cases in which the SSO aims at full participation, but type $\theta_i$ would reject such an SSO and enforce the market solution (the situation in Section 2). However, it also includes settings in which the SSO only aims at coordination among a subgroup of firms but wants type $\theta_i$ to participate.

To proceed we define three objects. First, let $I(\{\theta_j\}_{j\in N'\setminus i}|\theta_i) =: I_{\theta_i}$ be a distribution over the types of firms $j \in N' \setminus i$ conditional on firm $i$ being type $\theta_i$, where $N'$ is the set of firms expected to accept the mechanism with positive probability. That is, $I_{\theta_i}$ describes firm $i$'s information set regarding the participating firms conditional on $i$'s own type. Second, let $I^0_{\theta_i}$ be the information set of firm $\theta_i$ at the beginning of the game. Finally, let $v(\theta_i; I_{\theta_i})$ be $\theta_i$'s value of vetoing, that is, the expected continuation payoff from rejecting the SSO.

Our next result, Proposition 4, states that informational punishment is necessary to persuade type $\theta_i$ to participate in the SSO if $x_i(\theta_i) < v_i(\theta_i)$. Moreover, we show that, all else equals, informational punishment is sufficient if $x_i(\theta_i) \geq vex_{I_{\theta_i}}(v(\theta_i; I^0_{\theta_i}))$ where $vex_{I_{\theta_i}}(v(\cdot))$ is the convex envelope of $v(\cdot)$ with respect to the information set as defined below.

**Definition 1** (Convex Envelope)**.** The convex envelope w.r.t. to $I$, $vex_I(f(t, I))$, of a function $f$ is the largest function convex in $I$ that is (pointwise) smaller than $f$.

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

**Proposition 4.** *To persuade type $\theta_i$ to participate in an SSO with expected payoff $x_i(\theta_i) < v_i(\theta_i; I^0_{\theta_i})$ informational punishment is necessary. If in addition $x_i(\theta_i) \geq vex_{I_{\theta_i}}(v_i(\theta_i; I^0_{\theta_i}))$, then informational punishment is also sufficient to persuade $\theta_i$.*

The result shows that informational punishment is particularly useful when participation constraints are demanding.

**Definition 2** (Demanding Participation Constraints)**.** The participation constraint of type $\theta_i$ of firm $i$ is *demanding* if the value of vetoing at the prior $v_i(\theta_i; I^0_{\theta_i}) \neq vex_{I_{\theta_i}}(v_i(\theta_i; I^0_{\theta_i}))$.

**Corollary 1.** *Informational punishment has no effect if participation constraints are not demanding.*

**When can informational punishment guarantee full participation?** Given Proposition 4 it is natural to ask when informational punishment solves the participation problem. Here we provide a sufficient condition.

The answer to the question above is useful for two reasons. The first reason is a practical one. It facilitates finding an optimal SSO. If the designer of the SSO can exclude all SSOs that do not involve full participation from her consideration set, she has less SSOs to choose from which simplifies the design question. The second reason is normative. It explains a minimal flexibility on the acceptable institutions we should grant an SSO's designer if full-participation is desired.

To answer the question we take the perspective of the designer of an SSO. We describe a minimal requirement on the arsenal of SSOs available to the designer, i.e., institutional requirements an SSO needs to satisfy, such that the optimum among those can be implemented with full participation.

We want to emphasize that our sufficient condition for full participation at the optimum does not rely on any assumption about the SSO's objective. Thus, we also cover cases in which the SSO is designed to benefit some firms more than others. It even includes cases in which a single profit-maximizing firm designs the SSO. Moreover, we do not rely on commitment assumptions about the participating firms. That is, even if the firms cannot commit to obey the decisions of an SSO our results are valid.

The first requirement we impose on the set of potential SSOs is that they can replicate the *outcome* of the market solution.[22] Note that in our stylized model that assumption failed as the designer of the SSO was not allowed to reduce the joint surplus below 1. Consequently, she could not replicate the outcome of the market.

At first glance replicating the market seems to be sufficient for full participation even absent informational punishment. It turns out, however, that this conjecture is false (see Appendix B.2 or Celik and Peters (2011) for details). The reason is that no mechanism can get around the signaling value of a firm's veto and subsequent strategy adjustments.

The second requirement we impose is that if two SSOs, $M_1$ and $M_2$, are in the designer's arsenal, she can propose to implement a convex combination of $M_1$ and $M_2$. This assumption assures that the designer does not want firms to reject an SSOs with some probability to implement stochastic outcomes.[23]

[22] For example, SSOs should allow for the possibility that negotiations fail and firms cannot agree on a standard.

[23] For example, bargaining within an SSO about the licensing of patent rights might depend on the number of distributors that join the SSO. If say 2 distributors join, the SSO follows the rules of $M_1$. If instead 3 distributors join, it follows the rules of $M_2$. Suppose the designer prefers an outcome between $M_1$ and $M_2$. If

**Proposition 5.** *Given the two minimal requirements above, it is without loss of generality to focus on SSOs that imply full participation when informational punishment is available.*

# 4 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 is 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. The key feature is that the third party promises to "talk" herself once firms cannot coordinate.

Our findings offer several interpretations of real-world phenomenons. For example, they can rationalize strategic information leakage, risky product announcements that potentially turn into vaporware, or the release of beta versions. All these strategies may aid coordination serving as informational punishment tool. Firms commit to releasing an informative signal in the future. That way, competing firms are persuaded to cooperate on setting a standard.

Methodologically, our approach 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 coordination among firms. 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 to firms.

she cannot propose convex combinations of $M_1$ and $M_2$, the third distributor must be indifferent between joining and rejecting.

# Appendix

## A Proofs

### A.1 Proof of Lemma 1

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

### 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 between low-cost firms 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 between low-cost firms 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 between low-cost firms 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, $\rho_{-i}(l) = p^0_{-i}/(1-r)$ and $v_i(\Sigma^*, 1) = (1 - \rho_{-i}(l))\frac{(k-1)}{k} = (1 - r - p^0_{-i})(k-1)/(k(1-r))$. 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 4

*Proof.* Suppose $x(\theta_i) \in [vex_I(v_i(\theta_i; I^0), v_i(\theta_i, I^0))$. Then absent informational punishment type $\theta_i$ would reject the offer from the SSO.

We want to show that there is an informational punishment mechanism that persuades $\theta_i$ to participate. Firm $\theta_i$ participates if $x_i(\theta_i)$ is not smaller than the value of vetoing. Suppose the other firms can send a signal of arbitrary precision about their type distribution. Any such signal must be Bayes' plausible, that is, $\mathbb{E}[I(\theta_i)|\Sigma] = I^0(\theta_i)$. Using (the inverse of) standard concavification arguments, we know that $\mathbb{E}[v(\theta; I(\theta_i)|\Sigma] \geq vex_I(v(\theta; I^0(\theta_i)))$. If the type space is finite there is a signal $\Sigma$ such that the previous equation holds with equality, if the state spaces is infinite the expected value can be at least arbitrarily close to the convex envelope (see the online appendix of Kamenica and Gentzkow, 2011, for more details).

If $x_i(\theta_i) \geq v_i(\theta_i; I^0)$, $\theta_i$ participates without any persuasion through informational punishment, if $x_i(\theta_i) < vex_I(v(\theta; I^0(\theta_i)))$ informational punishment cannot persuade $\theta_i$ to participate. $\square$

### A.5 Proof of Proposition 5

The proof makes use of the general model outlined in Appendix B and is thus deferred to Appendix B.3.

## B A General Model

Here we provide a general model of SSOs. For notational convenience at this level of generality we use the language of mechanism design to do so. We allow for an arbitrary (finite) number of firms and an arbitrary (one-dimensional) type space. In addition, we allow for any market game. Moreover, the set of available SSOs is arbitrary too, but it can at least replicate the market outcome.

The market is an arbitrary exogenously given game of incomplete information. An SSO is an alternative game of incomplete information targeted at a subset of firms. The SSO is accepted if and only if all *targeted* firms decide to join. After its members interacted via the SSO, the remaining firms, if there are any, interact with the members of the SSO on the market. For each firm this interaction leads to some outcome that depends on private information. A decision rule, which maps actions (i.e., type reports) into outcomes, stacks these outcomes together.

Formally, we model this situation by applying the tools of mechanism design, in particular, the revelation principle. We are looking for one (abstract) mechanism in which all firms participate. That mechanism then directly implements the decision rule of the SSO-selection game described above. Informational punishment, however, is only directed at the targeted firms, as non-targeted firms cannot be persuaded to participate in the SSO. If one of these firms reject the mechanism, the decision rule that emerges after a veto in the SSO-selection game results.

Finally note that we model informational punishment 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.

### B.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 $\theta_{-i} := \theta \setminus \theta_i$, and define the marginal $I_i^0(\theta_i) := \int_{\Theta_{-i}} I(\theta_i, d\theta_{-i})$ with support $supp(I_i^0) \subseteq \Theta \setminus \theta_i$. This formulation covers both finite and convex type spaces.[24]

Throughout the paper an information structure $I$ is a commonly-known joint distribution over the state $\theta$. 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, $\theta_i$, 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 $\sigma$ 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, $\mu_\pi(\cdot|\theta) = \pi(\theta)$.

**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 $\pi_I^M$. Under this decision rule the expected utility of a truthfully reporting firm $i$ with type $\theta_i$ 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 $\pi_I^M$ 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 $\pi_I^M$.

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 $\pi_I^M$ is $I$-IC. Other than assuming existence of equilibrium under $\mathcal{I}^0$ we impose no further restrictions on $\Pi^M$.

**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 $\Pi$. Given $\pi$ and an information structure

[24] 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 7. For simplicity and to maintain the intuition from the binary example in Section 2, we state Proposition 7 assuming a finite type space. However, following Kamenica and Gentzkow (2011) a similar result can be obtained for a continuous type space.

$I$, 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 $\pi$ implements the decision rule $\pi_I := \pi \circ m_I : \Theta \to \Delta(Z)$ which is $I$-IC.[25]

The set of available SSOs, the collection $\Pi$, 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) $\Pi$ 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 $\Pi$. Thus, we do not restrict attention to mechanism-design problems in the classical sense. Instead we assume an exogenously given set of particular games, provided that replicating the market is part of this set. This assumption includes also the option of pure 'mediation' (Goltsman et al., 2009) within the market.

**Informational Punishment.** Finally, we assume that a signaling device $\Sigma$ 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 $\Sigma$ by $\sigma \in S$ and that of a particular $\Sigma_i$ by $\sigma_i \in S_i$.

**Timing.** At the beginning, firms learn their types and observe $\pi$. Then, they simultaneously send a message $m_i^\Sigma$ to $\Sigma$. 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 $\sigma$ 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 $\pi$.

**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 $\sigma$. 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,

[25] Although any decision rule in $\Pi$ represents a direct-revelation mechanisms, truthful implementation may not be guaranteed. Indeed, $\Pi$ 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.

all but first-node off path beliefs on deviators are derived via Bayes' rule. The remaining—off-path—beliefs are arbitrary.[26]

## B.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 $\pi$ 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 market solution.[27] 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, $\pi$, that all firms are expected to accept. Then, on the equilibrium path the SSO implements $\pi_{I^0}$. 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, $\pi_{I^0}$, 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.

## B.3 Proof of Proposition 5

In this part we highlight why informational punishment overcomes the issue of non-participation presented in Appendix B.2. We do so by presenting the proof of Proposition 5 which is constructive.

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

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

*Proof.* The proof is constructive. Take any SSO, $\pi$, 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 $\pi$ is vetoed given type profile $\theta$. Moreover, $\xi_i(\theta_i)$ is the likelihood that type $\theta_i$ of firm $i$ vetoes $\pi$ 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 $\Pi$ 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 $\pi_{I^a}$ 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 $\Pi$ is closed under convex combinations.

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

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 $\Sigma_i$. Thus, she disregards the realization $\sigma_i$. 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 $\Sigma_i$ 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 $\pi'$.

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

### B.4 Further Results

**Refinements.** Here we provide several additional results concerning the robustness of Proposition 5 with respect to the environment. The first concerns common equilibrium refinements, specifically

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

**Proposition 6.** *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.*

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

We show that the full-participation equilibrium constructed in the proof of Proposition 5, $(\Pi', \Sigma)$, 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 $\theta$. Thus, in any state $\theta$ 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 $\theta$ in which the mechanism is rejected in the veto equilibrium with positive probability. Now, for the same state, suppose that $\Pi'$ is rejected in the full-participation equilibrium, which is an off-path event. The resulting *off-path belief* on the deviator $\theta_i$ coincides with the *on-path belief* on the same $\theta_i$ 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 $\theta_i$ is credible in the sense of Grossman and Perry (1986) *and* off-path beliefs do not violate the intuitive criterion. □

For the special case that the designer can propose any game—i.e., she is a designer in the traditional sense of mechanism design—Proposition 5 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

**Implementability.** Next, 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. For these conditions 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 $\Sigma$ is a collection of random variables $\Sigma_i^V(m_i)$ where $V \in \mathcal{N}$.

Now, consider any decision rule $\pi_{I^0}$ associated with some $\pi \in \Pi$. Let $U_i(\theta_i)$ be type $\theta_i$'s on-path expected utility from $\pi_I^0$. 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 $\overline{\omega}_i(I) := \max_{\theta_i} \omega_i(I;\theta_i)$.

**Proposition 7.** *Consider an environment $(\Theta, I^0, \Pi^M)$ with $\Theta$ finite. The SSO $\pi_{I^0}$ 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 $\theta_i$, and some firm-dependent veto information structure $I^i$: $vex_{I^i}(\omega_i(I^i;\theta_i)) \leq 0$.*

*Proof.* Because $\Theta$ 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 $\sigma$ after $i$ vetoes induces $\omega_i(I^{i,\sigma}, \theta_i)$. Given $I^i$, any signaling device $\Sigma$ induces a lottery over belief systems with $E_\sigma[I^{i,\sigma}] = I^i$. Fix any function $\omega$. By Jensen's inequality a $\Sigma$ 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 $\omega$ 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 $\Sigma$. Thus, $\pi_{I^0}$ cannot be implemented with full participation. □

**Informed Principals.** Our next result concerns informed principle problems that is, the SSO is offered by one of the the firms. A 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.

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

*Proof.* Suppose there exists an equilibrium of the grand game such that different types of firm 0 propose different $\pi$s. Let $\mathcal{M}$ be the set of $\pi$s that are proposed with strictly positive probability. Let $\xi_0^\pi(\theta_0)$ denote the probability that firm 0 type $\theta_0$ 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 $\pi$ is vetoed, some rule in $\Pi^M$ results. Let the probability that $\pi$ is vetoed be $\xi^\pi$. Moreover,

$\xi_i^\pi(\theta_i)$ is the probability that $\theta_i$ vetoes $\pi$. The separate-and-veto equilibrium implements a $I^0$-IC decision rule, $\pi^E_{I^0}$. $\pi^E_{I^0} \in \Pi$ because $\Pi$ is closed under convex combinations.

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

We construct a signaling device $\Sigma$ to support acceptance of $\pi^E_{I^0}$. 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 $\Sigma$. Thus, the reason why no firm rejects $\Pi^E$ is the same as in the proof of Proposition 5. The only difference is that the signaling function also replicates the potential signal-by-mechanism-choice behavior of the principal, captured by $\Sigma_0$. □

**Informational Opportunism.** Finally, we revisit the idea of informational opportunism discussed in Section 2 in light of our general model.

We focus on a designer whose action space is remains to be the set of signaling devices, but who chooses $\Sigma_i$ *after* obtaining the reports. The following assumption guarantees this.

**Assumption 1** (No Fabricated Data)**.** The choice of signaling *device*, $\Sigma$, 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 $\sigma$.

**Definition 3** (Informational Opportunism)**.** The designer of the signaling device suffers from *informational opportunism* if she cannot commit to a signaling device $\Sigma$ 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 $\Sigma$ if she strictly prefers to verify her type to the lottery induced by $\Sigma$.

**Proposition 9.** *Suppose firms' types are independently distributed and the designer types' preferences are aligned. A signaling device, $\Sigma$, is implementable by a designer that suffers from informational opportunism if and only if* no type faces unraveling pressure*.*

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

Suppose type $\theta_{-i}$ deviates by announcing $\Sigma'$ which does not verify $\theta_{-i}$. Firms observe the deviation $\Sigma'$ and its realization $\sigma'$. 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 $\Sigma'$. If a realization $\sigma'$ occurs with probability 0 given a type $\theta_{-i}$, 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 $\Sigma'$ there always exists an off-path belief about the deviating designer that rationalizes $F^{\sigma'}$.

By assumption $\Sigma'$ does not verify $\theta_{-i}$. 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 $\Sigma$ is implementable under informational opportunism. $\square$

No-unraveling pressure is necessary because allowing for informational opportunism comes at a cost. In the restricted environment of Proposition 9 it is also a sufficient condition for immunity.

**Corollary 2.** *Suppose firms' types are independently distributed and the designer types' preferences are aligned. Then the results in Proposition 5 and 8 are immune to informational opportunism.*

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 9 applies.

**Corollary 3.** *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.*

We now turn to a weak form of informational punishment. The designer can commit to a signal $\Sigma$ prior to firms' reporting, but can choose to conceal its realization.

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

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

**Corollary 4.** *Suppose firms' types are independently distributed and the designer types' preferences are aligned. Proposition 5 and 6 to 8 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 5 and 6 to 8 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 5.** *Suppose firms' types are independently distributed and the designer types' preferences are aligned. Proposition 5 and 6 to 8 are immune to weak informational opportunism even when ambiguous about the designer's objective function.*

Corollary 4 and 5 are a corollary to Proposition 9. If the designer's preferences are aligned between types, $\Sigma$ 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.

# C 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.

## C.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*

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

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

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

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

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

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

By Proposition 2 in Siegel (2014) it is without loss of generality (in terms of the outcome) to restrict ourselves to constructing one equilibrium as all equilibria are payoff equivalent.[28]

Let $e_i$ be the chosen investment of firm $i$. Given the strategies of its opponent, $\sigma_{-i}$ 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.

[28] See below for the respective argument.

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

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

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

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

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

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

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 $\Delta_1$, 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.

□

## C.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 $(r, \bar{e}]$ for some $\bar{e} < 1$. 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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