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 discuss several business practices that can serve as a signaling device to provide that information and to effectively ensure coordination.

JEL Codes: L24, D83, O32, D21

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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 could have been 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, a standard setting organization (SSO) can at most grant a favorable outcome to 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 (see Taylor, 2001, ch. 2).

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 (see Taylor, 2001, ch.2). Preparing for the standard war, the TWG announced that they are going to analyze the two proposals.[2] 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*

[1]For a detailed timeline and further information see Taylor (2001) and Wolpin (2007). For the view of industry observers at the verge of the standard war see e.g. Variety (1995)

[2]See, e.g., their press release at `https://tech-insider.org/digital-video/research/1995/0503.html`.

tried to be as fair as possible.'[3] Second, the announcement implied that the TWG was going to release the outcome of their evaluation at a later date Wolpin (see 2007).

The TWG was 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 formal rules how the firms compete on the market in case they would not agree on a standard (the market solution). Instead, it influenced the expected information structure. Moreover, it did so by *announcing* its plans to produce a signal rather than producing the actual signal.[4]

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.[5]

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.

Our stylized model of the standard-setting process 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.

[3] Quote taken from Wolpin (2007).

[4] 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.

[5] 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.

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.

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 another firm 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 the competitor firm.

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 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. That is, the threat of informational punishment relaxes parties participation constraints. In turn, informational punishment does not need to be executed on the equilibrium path. 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 line with Farrell and Saloner (1985) we view a standard war as a contest between competing standards. Alternatively, firms can coordinate on an SSO that governs the patent rights.[6]

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. Under this assumption, concerns of informational opportunism as in Dequiedt and Martimort (2015) do not apply directly.

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

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

participate in the proposed SSO by threatening to release information *otherwise*. Thus, on the equilibrium path information is never provided. Instead, the threat to do so alone convexifies outside options. As a consequence, the availability of a communication channel alone fosters coordination, and persuasion occurs "tacitly."

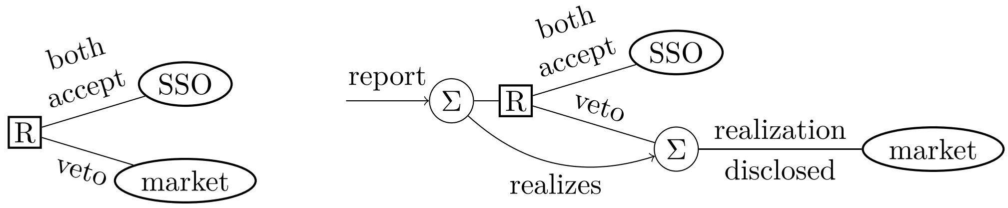
Gerardi and Myerson (2007) and Correia-da-Silva (2020) offer an alternative tool to induce participation. The main difference to our model is that in these models firms can verify neither a veto nor an acceptance decision. They propose a trembling device to relax participation constraints. The trembling 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 it is publicly observable who vetoed the mechanism. Instead, we propose informational punishment to discipline firms into participation. Different to trembling, informational punishment has no influence on the SSO itself.

The fact that full participation need not be optimal even for rich mechanism spaces is documented in Celik and Peters (2011). In an extension, we show that if the space of potential mechanism space is rich enough there is an SSO that is optimal *and* ensures full participation.

Our research also connects to our own work on information spillovers in mechanisms design (Balzer and Schneider, 2019, 2021). In Balzer and Schneider (2019) we 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 (2019) ignore these considerations by assuming a fixed outside option for each type.

Balzer and Schneider (2021) address alternative dispute resolution (ADR) in legal disputes. There, too, we consider a mechanism with a game as an outside option—litigation. However, the litigation model in Balzer and Schneider (2021) implies that utilities 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 (2019, 2021).[7]

[7] 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 all-pay auction (Szech, 2011; 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, Σ, to which firms report *before* (R). The signal realization becomes public only *after* (R).

2 Model

Players and Information. There are two risk-neutral firms who aim to establish a novel standard. Firm i, with $i \in \{1, 2\}$, possesses binary private information $c_i \in \{1, k\}$ about its technology to implement the standard.[8] We assume $k > 1$. The type is drawn according to a known, firm-specific distribution captured by $p_i^0 \in (0, 1)$, the ex-ante probability to be type $c_i = 1$. We use the convention that $p_i^0 \geq p_{-i}^0$. Moreover, normalizing one of the types to 1 is without loss as only the ratio between types matters.[9]

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 $r > 0$.[10] 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 $\max\{e_1, e_2\} \geq r$. Ties are broken at random. If both firms invest less than r no standard is implemented and firms receive 0 profits. For clarity we focus on the case of 'small' $r \in (0, 1/k)$. Extending to the remaining cases increases the number of case distinctions, but does not alter neither the intuition nor the basic results.

[8]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.

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

[10]As we see below, $r > 0$ implies that it requires a positive investment to win the standard war even if the competitor is ready to concede immediately. That cost induces a simple concavity in the payoff function that facilitates informational punishment. We provide further discussion and an alternative modeling choice at the end of Section 4. See also Proposition 5 below.

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 assume that cooperation makes the minimum investment r redundant, 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, $\Sigma_i : \{1, k\} \to \Delta\{l, h\}$, for each firm. The signaling device takes type reports as inputs and maps them into a distribution over the signal realizations $\sigma_i \in \{l, h\}$.[11] 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 signaling device, Σ_i^*.

Solution Concept. We are looking for perfect Bayesian equilibria (PBE). We assume Bayesian updating whenever possible. Failing that, we make the extreme assumption that an 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 $p_i = 1$.[12]

Relationship to the introductory example. 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 costs depend on the spillovers the respective camp has obtained while developing their standard proposal.

Informational punishment is a neutral third party that can provide an informative signal based on information provided by the firms. The TWG took that role. They made clear early on that their main goal was to avoid a standard war, but they were ex-ante agnostic about which side prevails. They scheduled an announcement in case the standard war was going to happen. The threat of releasing information was sufficient to induce the formation of the DVD Consortium and the TWG had no need to make their announcement.

After our analysis we provide other alternative interpretations and other business strategies that could take the role of informational punishment.

[11] Note that in this two firms version, correlation between Σ_i and Σ_{-i} do not matter. Indeed, firm i can avoid to report its type by refusing to participate in the SSO.

[12] The no-signaling-what-you-don't-know condition Fudenberg and Tirole (1988) of PBE is important for our analysis: firm i cannot influence its *own* belief on the non-deviator (nor alter common knowledge about it) by choosing to deviate. The assumption that the deviation of firm i triggers an off path belief of firm $-i$ *on* firm i that is extreme, $p_i = 1$, in contrast, is innocuous. No other (symmetric) off-path belief makes coordination on an SSO more likely. Issues with PBE arising in general sequential games (see, e.g., Sugaya and Wolitzky, 2018) do not occur our setting).

3 Analysis

We show that informational punishment increases the set of parameter values $\{r, k, p_1^0, p_2^0\}$ such that coordination on an SSO can be guaranteed. We proceed in steps. First, we analyze the model absent informational punishment. After that we introduce informational punishment to the model and compare results. We say a standard war is *inevitable* whenever it is impossible to propose an x_i that all types and firms accept with probability 1.

3.1 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. The standard war is a continuation game, and the information structure thus depends on the history of play.

To decide their investment into the standard war, firms use the public information structure and their private information c_i . A (mixed) strategy of firm i is a distribution of investments as a function of its cost. We denote it by the cumulative distribution $F_i^{c_i}(e_i)$. 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[13]

$$\max_{e \geq 0} \begin{cases} 0 & \text{if } e < r \\ F_i(e) - c_{-i}e & \text{if } e \geq r. \end{cases}$$

A key ingredient of the model is the two-sided private information. Because of private information *on both sides* standard wars can be inevitable even if—as in our case—every party has full commitment power upon agreeing to join the SSO and there *always* is an SSO that is a strict Pareto improvement. The reason for failure is mutual (and rational) optimism that one's own cost is likely lower than that of the competitor.

How much each firm invests into the standard war depends on (i) its own type, (ii) the belief about the competitor's type, and (iii) the equilibrium strategy of the competitor which depends on the competitor's belief. A firm's strategy is monotone in its type.

[13]We implicitly conjecture an atomless equilibrium distribution F_i in the description to abstract from ties. It turns out that indeed F_i has no atoms for any $e_i > r$ in any equilibrium and abstracting from ties is without loss (see also Siegel, 2014).

Moreover, if a low-cost (high-cost, respectively) firm expects a stronger competitor it invests more (less, respectively) itself. That, in turn, implies higher (lower, respectively) investment by the low-cost competitor and so on.

When firms initially decide whether to invoke the standard war by a veto, they foresee the behavior in the standard war. Thus they expect equilibrium behavior in the continuation game.[14] In general, deriving the payoffs in contest games with two-sided private information is notoriously cumbersome.[15] However, a special feature of the noise-free setting we employ is that the payoff functions are (piecewise) linear in the belief about the other player and thus a full characterization is possible. We provide it in appendix B.2.

Yet, our main exercise aims at characterizing when it is possible to coordinate on an SSO (and when not). It turns out that for that purpose it is sufficient to consider continuation games in which only one firm, firm i, surprisingly (that is, out off-equilibrium) vetoes the proposed SSO. In that case the belief on firm i is $p_i = 1$ by assumption whatever its true type. Thus, in what follows we restrict attention to information structures of the type $I := (p_i, p_{-i}) = (1, p_{-i})$.

Restricting to such a setting implies effectively only one-sided asymmetric information and therefore a much simpler setting which is what we consider in the main text.

It is instructive to discuss the strategic reasoning for each type of each firm. We begin with the non-vetoing firm $-i$.

The high-cost type of firm $-i$. Firm $-i$'s high-cost type believes its competitor to be of low-cost with probability one. Facing a strong competitor implies that it either stays out of the contest altogether and immediately concedes, or invests on (a neighborhood around) the minimum amount r. The latter can be optimal, because firm i has an incentive to only invest such a moderate amount itself if firm $-i$ concedes with sufficiently high probability.

The low-cost type of firm $-i$. Similar to its high-cost counterpart, the low-cost type of firm $-i$ also believes that firm i has low cost with probability one. Thus, whenever firm i moderately competes with firm $-i$'s high-cost type on (some neighborhood around) r, low-cost type $-i$ has an incentive to invest beyond that to beat firm i for sure. In turn, the highest investment firm $-i$ is willing to make has to match the highest investment that firm i is willing to make: any higher investment implies that firm $-i$ leaves money on the table.

The low-cost type of firm i. The behavior of the low-cost type of firm i depends on how likely it believes firm $-i$ has high cost. If firm $-i$ is likely to have high cost, the

[14]Note that even if entering the standard war is an off-path node, players correctly understand that this triggers an off-path information structure.

[15]Despite the enormous literature on contests, progress on two-sided private information has been sparse except for very special distributions (see Malueg and Yates, 2004; Fey, 2008, for such restricted results). This holds even for the binary case. See also the (indirect) proof of existence by e.g. Einy et al. (2015).

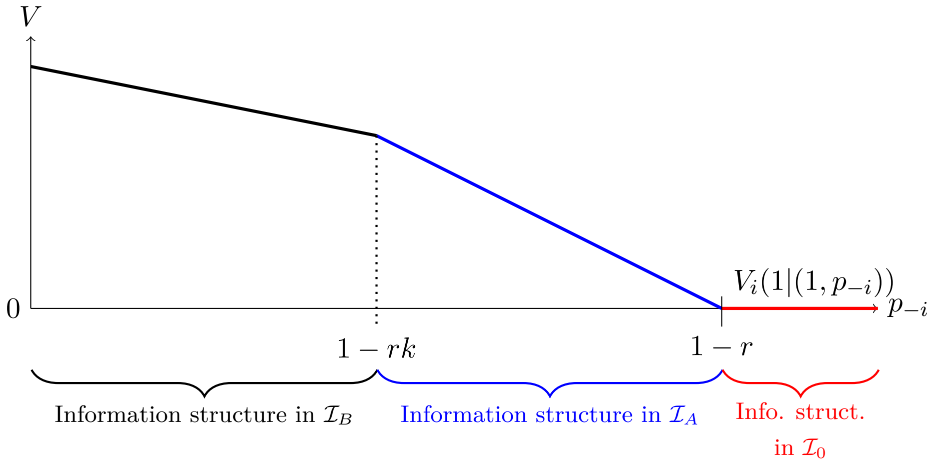


Figure 2: *Expected payoffs from the standard war.* Low-cost firm i's payoff $V_i(1|(1,p_{-i}))$, as a function of p_{-i}.

low-cost firm has a larger incentive to only provide moderate investments. Already then it wins many standard wars against high-cost firm $-i$. On the other hand, if firm $-i$ is likely to have low cost, competition is fierce and firm i is likely to invest more.

The high-cost type of firm i. Finally, we have to consider the high-cost type of firm i that mistakenly is considered to be a low-cost firm with probability one. As its competitor is surprised by that types existence, high-cost type i's behavior has no impact on equilibrium strategies. Depending on how fierce competition in the contest is, it either invests a moderate amount to win against high-cost firm $-i$ or concedes and stays out of the contest.

Calculating the equilibrium implies the following payoffs in the continuation game.

Lemma 1. *Consider a standard war under the information structure $I^i := (1, p_{-i})$. The expected payoff of player i, type c_i, $V_i(c_i|(1,p_{-i}))$ is:*

$$V_i(1|(1,p_{-i})) = V_{-i}(1|(1,p_{-i})) = \begin{cases} 0 & \textit{if } p_{-i} \geq 1-r \\ 1-p_{-i}-r & \textit{if } 1-r > p_{-i} \geq 1-rk \\ (1-p_{-i})\frac{k-1}{k} & \textit{if } 1-rk > p_{-i}. \end{cases},$$

$$V_i(k|(1,p_{-i})) = \begin{cases} 0 & \textit{if } p_{-i} \geq 1-rk \\ (1-kr-p_{-i})\frac{k-1}{k} & \textit{if } 1-rk > p_{-i} \end{cases},$$

$$V_{-i}(k|(1,p_{-i})) = 0.$$

If both firms are likely to have low cost, $p_{-i} > 1-r$, competition is fierce and rents are fully dissipated. We refer to this regime as $\mathcal{I}_0$. If firm $-i$ has an intermediate likelihood of having low cost, $p_{-i} \in [1-rk, 1-r]$, firm i's low-cost type reduces investment as it wins against a high-cost firm $-i$ with certainty. Competition is less fierce and low-cost types have positive expected payoffs. We refer to this regime as $\mathcal{I}_A$. If firm $-i$ is likely to have low cost $1 - rk > p_{-i}$, firm i's likelihood to offer only the minimum investment is so large that a high-cost firm $-i$ has an incentive to invest. We refer to this regime as $\mathcal{I}_B$.

Expected payoffs are linearly decreasing in p_{-i} within each region. Stronger competitors imply fiercer competition; because the contest is frictionless the marginal effect of an increase in a low-type's likelihood is constant. However, changes in behavior imply a change in the slope of the payoffs when moving from one region to another. Figure 2 illustrates these breaks. If p_{-i} is high, $p_{-i} > 1 - r$, the marginal payoff from an increase in p_{-i} is 0. Rents are fully dissipated in any way. For lower levels of p_{-i}, firm i's payoff decreases in its competitor's expected strength. If p_{-i} is low, $p_{-i} < 1 - rk$, competition becomes fiercer as p_{-i} increases because low-cost types of firm $-i$ increase their investment. Yet high-cost types of firm $-i$ remain absent and provide an "easy win" for firm i. Once p_{-i} crosses the threshold $1 - rk$, however, the high-cost type of firm $-i$ joins the competition and increases its (expected) investment as p_{-i} increases. The decline in firm i's payoff accelerates.

Accepting a Proposal. We now turn to the decision whether to veto a given proposal x_i. We keep 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. If firm i accepts the SSO it receives the (continuation) payoff x_i and the game ends. In contrast, if firm i vetoes the SSO, the standard war is triggered, and Lemma 1 provides firms' continuation payoffs.

Suppose firm i vetoes. Firm $-i$ concludes that firm i is 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 $-i$. Firm i's outside option to accepting the proposed SSO is thus $v_i(c_i; p^0_{-i}) := V_i(c_i|(1, p^0_{-i}))$.

We begin with a simple, yet important lemma that describes the high-level relationship between the occurrence of a standard war and the parties outside option.

Lemma 2. *A standard war is inevitable if and only if* $v_1(1; p^0_2) + v_2(1; p^0_1) > 1$.

Proof. The reasoning is intuitive. Low-cost types can always mimic high-cost types and thus $v_i(1; p^2_{-i}) \geq v_i(k; p^2_{-i})$. 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. $\square$

Applying Lemma 2 to our setting determines the parameter specifications for which a standard war is inevitable. Note that both firm 1 and firm 2 can veto an SSO. We thus have to take into account which of these vetoes triggers which type of standard war (in terms of information structures I^i). Recall our convention that $p^0_i \geq p^0_{-i}$. The next proposition determines the parameter regions for which a standard war is inevitable. Figure 3 provides the corresponding illustration.

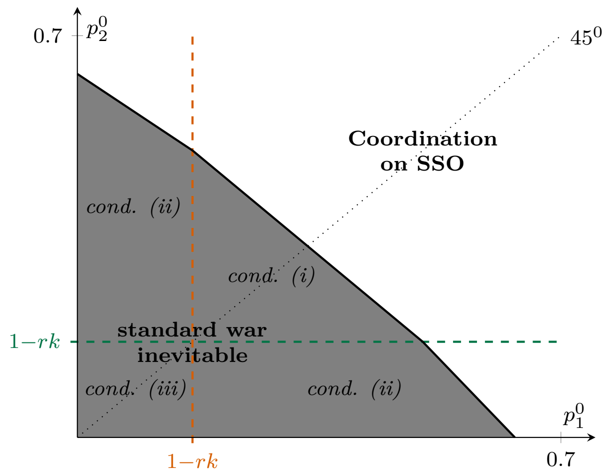


Figure 3: *Results without informational punishment.* The shaded area depicts the area in which a standard war is inevitable. Solid lines depict the relevant conditions from Proposition 1. The thin dotted line is the 45^0 degree line of symmetric distributions. The thick dotted lines jointly determine which condition applies. In the left bottom corner, $p_i^0, p_{-i}^0 < 1-rk$ and condition (iii) applies.[a] In the bottom right and top left condition (ii) applies. In the top right, condition (i) applies. In this example $r = 1/6$, $k = 5$.

[a] In this example, the left bottom area is entirely shaded, i.e., the second inequality in condition (iii) implies the first.

Proposition 1. *A standard war is inevitable if and only if at least one of the following (mutually exclusive) conditions holds*

(i) $1 - 2r > p_1^0 + p_2^0$ *and* $p_{-i}^0 \geq 1 - rk$,

(ii) $1 - (r + p_i^0)\frac{k}{k-1} > p_{-i}^0$ *and* $p_i^0 \geq 1 - rk \geq p_{-i}^0$, *or*

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

The intuition behind Proposition 1 is as follows. If the likelihood that the competitor 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 competitor, the sum of expected payoffs from a veto is larger than 1, making at least one type of one firm veto the proposal.

A corollary to Proposition 1 is that when high and low cost are close to each other, $k < 2$, coordination is always feasible. The intuition behind that statement is that failure to coordinate originates in mutual optimism of the two low-cost types. Both believe that with high probability they are able to win the standard war at low investment levels. When differences in cost are small, that statement does not hold even if the competitor is a high-cost type for sure. Marginal cost of $k < 2$ are not high enough to reduce the high-cost type's investment sufficiently much.

3.2 With Informational Punishment

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

1. Each firm privately learns its type realization, the SSO announces the shares (x_1, x_2);

and the signaling devices Σ_i are publicly announced;

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

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

4b. Otherwise, all veto decisions and realization σ_i are publicly announced. Firms engage in a standard war.[16]

Different to the timing in Section 3.1, firms now have the option to report to a given signaling device, Σ_i. For now, we assume that Σ_i is known and committed. That is, the signaling device takes a firm's report as input and maps it to an outcome, σ_i, according to Σ_i. Then, it truthfully reveals that outcome upon a veto. In what follows we characterize the triple $(\Sigma_1, \Sigma_2, x_1)$ that maximizes the likelihood that an SSO is implemented.

We are going to refer to the realization $\sigma_i = l$ ($\sigma_h = h$) 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. Our discussion focuses on the case in which firm i contemplates to veto the SSO.

The Standard War. We conjecture that firms report truthfully to Σ_i on the equilibrium path and verify our conjecture later. A veto by firm i leads to an off-path belief $p_1 = 1$. Thus, the signal realization *about* firm i, σ_i, provides no additional information.[17]

Suppose the signal about firm $-i$ has realized as σ_{-i}. It carries information about firm 2 (the non-deviator). Firm 1 (the deviator) uses that information to form a posterior belief $p_{-i}(\sigma_{-i})$. The information structure is $I = (1, p_{-i}(\sigma_{-i}))$. The continuation payoffs follow from Lemma 1.

Consistent Signals. We now turn to the properties of the signaling device. Whatever signal realizes, firm i forms a posterior. Posteriors are consistent with the prior. Consistency is a direct consequence of the firm's updating process. Firm 1 uses its knowledge about the mapping Σ_{-i}, the prior p^0_{-i}, and the realization σ_{-i} and updates the belief about its competitor to a posterior p_{-i} via Bayes' rule.

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

$$\rho_{-i}(\sigma_{-i} = l)p_{-i}(\sigma_{-i} = l) + \rho_{-i}(\sigma_{-i} = h)p_{-i}(\sigma_{-i} = h) = p^0_{-i}. \tag{1}$$

The ex-ante likelihood that $\sigma_{-i} = l$ realizes is

$$\rho_{-i}(\sigma_{-i} = l) = p^0_{-i}\rho_{-i}(\sigma_{-i}|c_{-i} = 1) + (1 - p^0_{-i})\rho_{-i}(\sigma_{-i}|c_{-i} = k), \tag{2}$$

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

[17] Note that since any firm can report any cost to the signal Σ, even a 'revelation' that firm i has reported high cost does not influence firm $-i$'s off-path belief. She simply assumes that firm i had misreported to Σ and is the low cost type with probability 1.

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

The optimal Signaling Device. We now state the properties of the optimal signaling device, Σ^*. Thereafter, we highlight the economics involved in finding Σ^*.

Lemma 3. *The signaling device that minimizes the probability of a standard war, Σ^*, has the following properties: the high signal is fully revealing, that is, $p_{-i}(\sigma_i = h) = 0$ whereas the low signal induces interior belief $p_{-i}(\sigma_i = l) = 1 - r$.*

We now discuss the construction of Σ^*. The corresponding formal arguments are in the proof of Lemma 3. Fix a signaling device about firm $-i$, Σ_{-i}. Its properties are commonly known and so is the lottery over posteriors 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 i of $v_i(1; \Sigma) := \rho_{-i}(\sigma_{-i}{=}l)v_i(1; p_{-i}(l)) + \rho_{-i}(\sigma_{-i}{=}h)v_i(1; p_{-i}(h))$.

Why is Σ^* helpful? The standard war is a strategic game. The additional information firm i receives about firm $-i$'s cost type, σ_{-i}, changes its equilibrium strategy. In turn, firm $-i$ 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 aggressive investments of firm $-i$. Rents are fully dissipated. Firm 1 is worse off than under the prior. However, if the high signal realizes, firm i is better off than under the prior. Its competitor is a high-cost type for sure. Importantly, both the high-cost type of firm $-i$ and the deviator, firm i, 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 i obtains a payoff of $1 - 1/k$. Because payoffs are non-linear in information, the loss firm i expects from signal $\sigma_{-i} = l$ outweighs the gain it expects from signal $\sigma_{-i} = h$. That is, the continuation payoff v_i is concave in p_{-i} in the relevant region. From firm i's perspective given two information structures, the expectations over continuation payoffs is less than the continuation payoff of the expected information structure. Thus, Σ_{-i} reduces the continuation payoff v_i.

Graphically, we obtain the optimal signal structure directly from Figure 4. Three observations lead to the result. (i) Any posterior $p_{-i}(\sigma_{-i})$ corresponds to a posterior value of vetoing which is on the graph of $v_i(1; p_{-i}(\sigma_{-i}))$, (ii) any signal structure is a mean preserving spread around the prior, p^0_{-i}, and (iii) the signal structure implies an expected value of vetoing that is the convex combination of the two posterior values, $v_i(1; p_{-i}(\sigma_{-i}))$, with $\rho_{-i}(l)$ as the weight. Combining these three observations immediately leads to the result. Geometrically, $v_i(1; \Sigma)$ has to be on the line connecting the two post-realization payoffs $v_i(1; p_i(l))$ and $v_i(1; p_i(h))$. Moreover, $v_i(1; \Sigma)$ is the value of that line evaluated at the prior p^0_{-i}. The dashed line in Figure 4 represents that line under the optimal signal.

Why is Σ^* optimal? The graphical analysis delivers the intuition. We want to minimize $v_i(1; \Sigma)$ over Σ. The smallest v_i the signal can induce is the largest convex function weakly below $v_i(1; p_{-i})$. The dotted line in Figure 4 provides that function for information

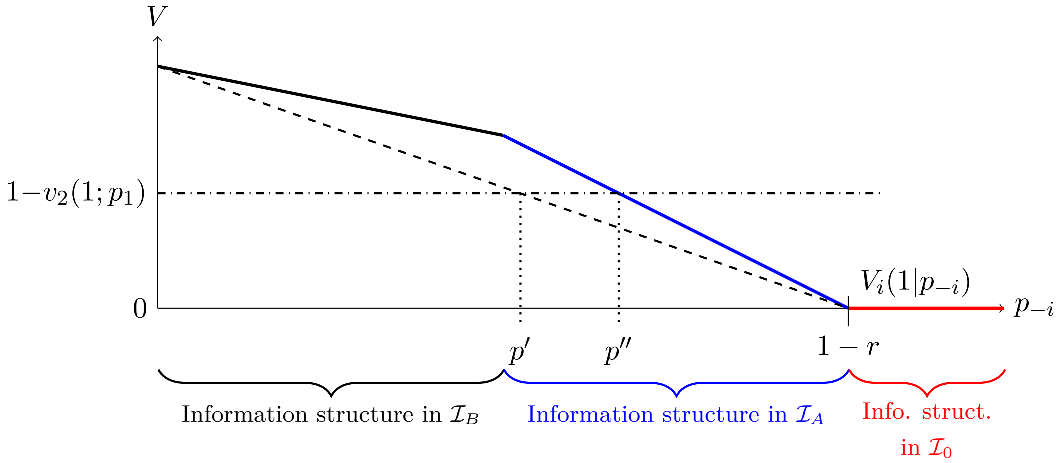


Figure 4: The value of vetoing for firm 1 given firm 2 assigns a probability p_1 to firm 1 having cost 1. The dashed line denotes the function's convex envelope. The dot-dashed depicts the residual resources after paying the minimum share to firm 2. For $k = 5$, $p_1 = 1/3$ and $r = 1/6$, it follows that $p' = 7/24$ and $p'' = 1/3$.

structures $\mathcal{I}_A$ and $\mathcal{I}_B$. The optimal function picks the two extreme points in that region. One is $p_{-i} = 0$ and the other is $p_{-i} = \min\{1 - r, p_i\}$. Note that $p_{-i} = 1 - r$ because the veto belief $p_i = 1$.

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 competitor 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.[18]

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 war is inevitable if and only if*

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

The parameter space in which the standard war in inevitable under informational punishment is strictly smaller than without informational punishment.

Figure 5 graphically illustrates that informational punishment enlarges the parameter space in which coordination is possible. Observe that —provided there was an issue in

[18]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.

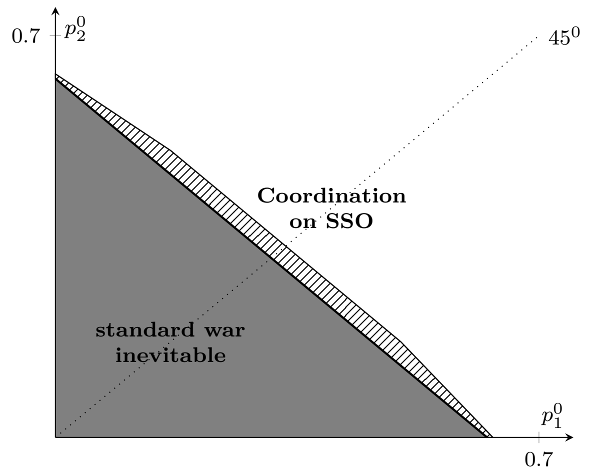


Figure 5: *Results with informational punishment.* The shaded area depicts the area in which a standard war is inevitable. The hatched area denotes in which coordination is only possible under informational punishment.

the first place—coordination is facilitated for any p^0_{-i} in the example of Figure 5. That is, even as $p_{-i} \to 0$ informational punishment improves coordination.

Informational punishment shifts firms' beliefs about the state of the world. The shift has two effects. The first is *distributional.* The larger p_i, the more likely it is that 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 investment increases over-proportionally 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 5 informational punishment is not sufficient to guarantee participation in our simple model. If the set of potential SSO mechanisms is rich enough, coordination on an SSO is always possible, but only if informational punishment is available. Proposition 5 in Section 5 provides the respective result.

4 Interpretation and Discussion

Informational punishment is a simple yet powerful signaling device. It requires the following features only. 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.

4.1 When is informational punishment useful?

In the following, we fix an SSO and the associated expected outcome $x_i(c_i)$ awarded to each participating firm i with cost c_i. We are interested in a case in which a specific firm's cost-type c_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 c_i to participate?

To proceed we recall four objects. First, p_{-i} is the belief that firm i holds about firm $-i$'s cost distribution. Second, p^0_{-i} is the ex-ante prior about said cost distribution firm i holds at the beginning of the game. Third, p^v_i is the belief that firm $-i$ holds about firm i conditional on firm i vetoing the SSO. Finally, $V_i(c_i|(p^v_i, p_{-i})$ is the value of vetoing for firm i with cost c_i, that is, the expected continuation payoff from rejecting the SSO.

Our next result, Proposition 3, states that informational punishment is necessary to persuade cost-type c_i to participate in the SSO if $x_i(c_i) < V_i(c_i|(p^v_i, p_{-i}))$. Moreover, we show that, all else equals, informational punishment is sufficient if $x_i(c_i) \geq vex_{p_{-i}}(V(c_i|(p^0_i, p^0_{-i})))$ where the latter is the convex envelope of $V(\cdot)$ with respect to p_{-i}.

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

$$vex_y(f(t; y)) := \sup\{g_t(y) : g_t(y) \leq f(t; y) \text{ and } g \text{ convex}\}.$$

Proposition 3. *To persuade cost type c_i to participate in an SSO with expected payoff $x_i(c_i) < V_i(c_i|(p^0_i, p^0_{-i}))$ informational punishment is necessary. If in addition $x_i(c_i) \geq vex_{p_{-i}}(V_i(c_i|(p^0_i, p^0_{-i})))$, then informational punishment is also sufficient to persuade c_i.*

4.2 Alternative Interpretations

We now discuss a set of real-world business strategies that could serve as (de-)centralized informational punishment mechanisms as an alternative interpretation of our model.

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.

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.[19]

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.[20]

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

[19] In some of the interpretations presented below the signal produces verifiable evidence, while our baseline model assumes that reports to Σ_i are non-verifiable. It turns out that in our model there is no qualitative difference between the two since the incentive constraint to truthfully report to Σ_i is non-binding in equilibrium and a potential deviator has no incentive to fully reveal its cost if they are high.

[20] 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).

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.[21] 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).

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.

4.3 Underlying Model Assumptions

The assumption on a two-player, two-cost-type model is purely technical and for expositional convenience. Increasing the type-space to a (finite) number of costs complicates the algebra, but does not alter intuition. In the following, we discuss the underlying economic assumptions that we made in greater detail. We assume that vetoes become public. Yet,

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

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.[22] Without the minimum investment, a frictionless standard war would not leave any scope for informational punishment, because expected payoffs would be linear in p_{-i}. However, introducing other frictions, e.g., noise in determining the winner of the standard war, restores our arguments informational punishment. See **??** for an example.

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.

5 Extensions

In this part we provide three extensions of our model.

1. We introduce informational opportunism, that is, the designer of informational punishment behaves strategically too.
2. We allow for more sophisticated mechanisms than the take-it-or-leave-it offer x_i in the baseline model.
3. We discuss the case of more than two firms.

5.1 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 Σ. Dequiedt and Martimort (2015) show that such informational opportunism can overturn the outcome

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

derived under commitment.[23]

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

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

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

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

Proposition 4. *Informational Punishment is immune to informational opportunism, i.e. the optimal signals, Σ_i^{EPIC} and Σ_i, in the two scenarios coincide, $\Sigma_i^{EPIC} = \Sigma_i$.*

5.2 Sophisticated Mechanisms

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 4, 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.

How do the benefits of informational punishment generalize to richer SSOs? In such a richer setting 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. The reason is that informational punishment operates off the equilibrium path by punishing a firm not participating in an SSO but becomes irrelevant once all firms accepted an SSO.[24]

[23] The TWGs press releases (see Taylor (2001) for a discussion) arguably suggest that the TWG was indeed a strategic designer and therefore may have suffered from informational opportunism.

[24] A richer way to model an SSO might be to allow for negotiations between many firms. The outcome of those negotiations are then either a common standard (with a distribution of royalties between firms) or a standard war. In such a setting, firms' participation constraints are not necessarily trivial: firms' behavior during those negotiations can reveal part of their private information. This revealed information, in turn, affect firms behavior in case a standard war occurs and thus their willingness to accept an agreement. In such a setting, informational punishment incentivizes firms to participate in these negotiations in the first place.

We extend the definition of an SSO as follows. In its most abstract form, an SSO is a one-shot mechanism. A firm accepts that mechanism by reporting its type $\hat{c}_i \in \{1, k\}$. If both firms report their type, the report profile probabilistically determines which of the following two outcomes realizes: (i) they agree on a share x_i (in case a standard ward is avoided), or (ii) a disagreement, that is, the decision that the standard war takes place. Formally, the definition is as follows

Definition 2. The set of SSOs, $\mathcal{SSO}$, is the set of all mappings

$$SSO = (\gamma, x_1, x_2) : \{1, k\}^2 \to [0, 1] \times [0, 1] \times [0, 1]$$

such that $x_1 + x_2 \leq 1$.

In the case of an agreement, which happens with probability $\gamma(\hat{c}_1, \hat{c}_2)$, a firm's payoff is equal to its attributed settlement share. In case of disagreement, which happens with the remaining probability, each firm uses the knowledge about its own type report together with its competitor's commonly-known equilibrium reporting strategy, to update on the (on-path) information structure, $I = (p_1, p_2)$. A firm's (expected) payoff from the disagreement outcome is thus given by $V_i(c_i|\hat{c}_i, I)$.[25]

The set $\mathcal{SSO}$ describes all possible normal-form games that determine the standard when the outside option is the market solution. Observe that any SSO $\in \mathcal{SSO}$ with $\gamma = 1$ is the market solution itself. Thus in principle we allow for the SSO to replicate the market.

Thus, in equilibrium a firm's expected payoff from joining the SSO is

$$\begin{aligned} &p^0_{-i}[\gamma(c_i, 1)x_i(c_i, 1) + (1 - \gamma(c_i, 1))V_i(c_i|c_i, I)] \\ &+(1 - p^0_{-i})[\gamma(c_i, k)x_i(c_i, k) + (1 - \gamma(c_i, k))V_i(c_i|c_i, I)], \end{aligned}$$

where I depends on γ via Bayes' rule. Importantly, given an informational-punishment device Σ, a firm's expected payoff from vetoing the SSO is the same as in Section 3.

Deriving the optimal mechanism requires to take a stand on the designer's objective. It is in general complicated and beyond our scope here. In Balzer and Schneider (2021) we construct a disagreement-minimizing mechanism for a version of our moder with $r = 0$ in a different context. Here we focus on the question whether informational punishment helps in such an extended setting.

Celik and Peters (2011) show that there are cases in which the optimal mechanism involves on-path rejection by some players or cost types. The reason is that parties have an incentive to use rejections as a signal of their type and thus the revelation principle fails when the outside option to the mechanism is a non-cooperative game. Here we show that if we augment the setting by informational punishment, the concerns of Celik and Peters (2011) become obsolete: An optimal full-participation mechanism always exists.

[25] $V_i(c_i|\hat{c}_i, I)$ depends explicitly on $\hat{c}_i$ as a firm might deviate from equilibrium.

Proposition 5. *Suppose the set of mechanisms is $\mathcal{SSO}$. It is without loss of generality to focus on those SSOs that imply full participation when informational punishment is available.*

5.3 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. 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. Here we address two setting. First that of consortia formation prior to standard development, second an SSO that has to coordinate among multiple firms.

Consider the stage in which firms start to think about whether to form a consortium.[26] At that stage each individual firm takes into account that the industry will eventually settle for one standard once the consortia formatted. 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.

Once formed, the consortium competes with the remaining firms in a second stage. Yet, a consortium still provides each participating firm with an expected surplus $x_i(c_i)$ that depends on its private information. That expected surplus has to be larger than a firm's value of vetoing $v_i(c_i; I)$, which may be the (expected) payoff from joining the *competing* standard. In particular, if key players are expected to not participate, $x_i(c_i)$ decreases and other firms may want to stay out of 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 3. If it does, and firm i finds it beneficial to make firm j participate, it has an incentive to provide informational punishment.

A similar case applies to consortia that are formed to develop a standard.[27] Such consortia act as standard-developing organizations (SDOs). In that case the ratification of the SDOs standard replaces our participation decision. The SDO decides on the standard and the distribution of royalties of included patents and patent holders vote whether to accept the proposal. If they do, the standard is implemented and patent holders obtain their payoff x_i. If one rejects, the standard is modified and does not include the proposed patent. Now the patent holder has to ensure to prevail on the market against alternative specifications. Its expected payoff is $v_i(c_i; I)$ which depends on the belief about the power of the patent holders technology compared to the alternatives. Informational punishment

[26] In the introductory example such consortia were the MMCD camp around Sony and Philips and the SD camp around Toshiba and Time Warner.

[27] Examples include the World Wide Web Consortium (W3C), the Internet Engineering Task Force (IETF), the Institute of Electrical and Electronics Engineers (IEEE), or the European Telecommunications Standards Institute (ETSI).

may help to discipline ratification.

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 independent of 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 scenarios an industry consists of n firms. Depending on the context, an SSO (consortium, or SDO) 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 firms' 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.[28] A firm only joins an SSO if its continuation payoff from that action, $x_i(c_i)$, is larger than the value from not joining the SSO a payoff, $v_i(c_i; I)$, that depends on equilibrium reasoning and the implied information structure.

6 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

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

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.

Appendix

A Proofs

A.1 Proof of Lemma 1

Proof. The proof is a direct application of Siegel (2014). We present the full proof (including all other cases) in appendix B. □

A.2 Proof of Proposition 1

Proof. By Lemma 2 a standard war is inevitable if $v_1(1; p_2^0) + v_2(1; p_1^0) > 1$. Lemma 1 determines the relevant payoffs. The result follows from the respective calculations when using $p_i^0 \geq p_{-i}^0$. We discuss case 0 for completeness only.

Case 0: $p_i \geq 1 - r$**.** A veto by firm $-i$ implies a standard war under regime $\mathcal{I}^0$. She thus expects a payoff of 0 from vetoing. Promising the entire surplus to firm i is incentive compatible and guarantees coordination

Case 1: Assume $p_i^0, p_{-i}^0 \in [1 - rk, 1 - r]$**.** A veto by any firm implies a standard war under regime $\mathcal{I}^A$ with associated payoffs $v_i(1; p_{-i}^0) = 1 - p_{-i}^0 - r$ and $v_{-i}(1; p_i^0) = 1 - p_i^0 - r$. The sum is larger 1 if $p_1^0 + p_2^0 < 1 - 2r$ which implies condition (i).

Case 2: Assume $p_i^0 \geq 1 - rk > p_{-i}^0$**.** A veto by firm i implies a standard war under regime $\mathcal{I}^B$ while a veto by firm i implies regime $\mathcal{I}^A$. The corresponding payoffs are $v_i(1; p_{-i}^0) = (1 - p_{-i}^0)\frac{k-1}{k}$ and $v_{-i}(1; p_i^0) = 1 - p_i^0 - r$. The sum is larger 1 if $p_{-i}^0 < 1 - (r + p_i^0)\frac{k}{k-1}$ which is condition (ii).

Case 3: Assume $1 - rk \geq p_i$**.** A veto by any firm implies a standard war under regime $\mathcal{I}^B$. The corresponding payoffs are $v_i(1; p_{-i}^0) = (1 - p_{-i}^0)\frac{k-1}{k}$ and $v_{-i}(1; p_i^0) = (1 - p_i^0)\frac{k-1}{k}$. The sum is larger 1 if $p_i^0 + p_{-i}^0 < \frac{k-2}{k-1}$ which implies condition (iii). □

A.3 Proof of Lemma 3

Proof. Note first that the standard war minimizing signaling device, Σ_i^*, minimizes the payoffs of the low-cost type of firm i.

Fix $V_i(p|(1, p_{-i}))$ which is concave on $p_{-i} \in [0, 1 - r]$.[29] The following lemma proves that concavity is sufficient for the desired signal properties.

[29] It is concave because there is at most a switch from regime $\mathcal{B}$ to regime $\mathcal{A}$ as p_{-i} increases by Lemma 2. The payoff is piecewise linear decreasing with more negative slope in regime $\mathcal{I}^A$ compared to regime $\mathcal{I}^B$.

Lemma 4. *Suppose $f : [0,1] \mapsto \mathcal{R}$ is concave on $[a,b] \subset [0,1]$. Then, there exists an optimal signaling function putting mass on a and b only.*

Proof. For given $\bar{x} \in (a,b)$ we need to solve the following minimization problem:

$$\min_{x_n, \lambda^n \in [0,1]} \sum_n \lambda^n f(x_n),$$

subject to the constraints that $\sum_n \lambda^n x_n = \bar{x}$, $x_n \in [a,b]$, and $\lambda^n \geq 0$ such that $\sum_n \lambda^n = 1$.

Take any such $\{x_n\}_n$ with implied λ^n. The solution value of the minimization problem is

$$\sum_n \lambda^n f(x_n).$$

Now note that because $[a,b]$ is the convex hull generated by the points a and b, for each x_n there exists $\alpha^{x_n} \in [0,1]$ such that $x_n = \alpha^{x_n} a + (1-\alpha^{x_n})b$. Substituting into the solution value this becomes

$$\sum_n \lambda^n f(x_n) = \sum_n \lambda^n [f(\alpha^{x_n} a + (1-\alpha^{x_n})b)] \geq \sum_n [\lambda^n \alpha^{x_n} f(a) + \lambda^n (1-\alpha^{x_n}) f(b)],$$

where the last inequality follows from concavity of f.

Next, note that $\bar{\lambda} \equiv \sum_n \lambda^n \alpha^{x_n} \geq 0$ as $\alpha^{x_n}, \lambda^n \geq 0$. Moreover, $1-\bar{\lambda} = 1 - \sum_n \lambda^n a^{x_n} = \sum_n \lambda^n (1-\alpha^{x_n}) \geq 0$, where we used that $\sum_n \lambda^n = 1$. Thus, $\bar{\lambda} \in [0,1]$. Finally, note that $\bar{\lambda} a + (1-\bar{\lambda})b = \sum_n \lambda^n [\alpha^{x_n} a + (1-\alpha^{x_n})b] = \sum_n \lambda^n x_n = \bar{x}$. Thus, choosing two signals a and b with weights $\bar{\lambda}$ is a feasible solution for the minimization problem.

□

□

A.4 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 $v_i(1; \Sigma^*) = (1 - \rho_{-i}(l))\frac{(k-1)}{k} = (1 - r - p^0_{-i})(k-1)/(k(1-r))$. Moreover, $\sum_i v_i(\Sigma^*, 1) > 1$ if and only if

$$(2(1-r) - p^0_1 - p^0_2)\frac{(k-1)}{k(1-r)} > 1 \Leftrightarrow \frac{(1-r)(k-2)}{k-1} > p^0_1 + p^0_2.$$

The condition derived must include than the (joint) condition derived in Proposition 1. The reason is that an uninformative signal device is always feasible replicating the situation without informational punishment. Since Σ^* is chosen optimally, the claim trivially holds. However, the parameter space for which a standard war is inevitable is in fact *strictly* smaller under informational punishment, that is, under the optimal device Σ^*.

Comparing the condition from Proposition 2 with the three conditions from Proposition 1 implies directly that the condition in Proposition 2 is stricter than (i) and (iii) independent of p^0_i, p^0_{-i}. The condition from Proposition 2 is stricter than condition (ii) if

$1-2r-p_i > 0$ which holds whenever condition (ii) applies because the LHS of condition (i) and (ii) respectively intersect at $p_1 = 1 - rk$ with condition (ii) having the more negative slope. Since both are linear, this implies that for $p_1 > 1 - rk$ condition (ii) is weaker than the condition from Proposition 2. That in turn implies that the Proposition 2 is indeed stricter which proves the claim (see Figure 3 for an illustration). □

A.5 Proof of Proposition 3

Proof. Suppose $x(c_i) \in \Big[vex_{p_{-i}}(V_i(c_i|(p_i^0, p_{-i}^0))), V_i(c_i|(p_i^0, p_{-i}^0))\Big)$.

Absent informational punishment type c_i would reject the offer from the SSO.

We want to show that there is an informational punishment mechanism that persuades c_i to participate. Firm c_i participates if $x_i(c_i)$ 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, $\sum_{\sigma_{-i}\in\Sigma_{-i}} \rho_{-i}(\sigma_{-i})p_{-i}(\sigma_{-i}) = p_{-i}^0$. Using (the inverse of) standard concavification arguments, we know that $\mathbb{E}_{p_{-i}}[V_i(c_i|(p_i^v, p_{-i}(\sigma_{-i}))|\Sigma_{-i}] \geq vex_{p_{-i}}(V_i(c_i|(p_i^0, p_{-i}^0)))$.

If $x_i(c_i) \geq V_i(c_i|(p_i^0, p_{-i}^0))$, c_i participates without any persuasion through informational punishment, if $x_i(c_i) < vex_{p_{-i}}(V_i(c_i|(p_i^0, p_{-i}^0)))$ informational punishment cannot persuade c_i to participate. □

A.6 Proof of Proposition 4

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 Σ_i^{EPIC} which is identical to Σ_i constructed above.

Consider first the *low* type. She is indifferent between any mapping that does not increase the value of vetoing for a low-cost deviator. That is, any signal that ensures $p_2(\sigma_i^{epic}{=}l) \geq 1 - r$ is incentive compatible. By announcing the Σ_i we constructed under full commitment, she makes sure that the low signal realizes with probability 1.

Next consider the *high* type. She wants to pool with the *low* type in the most credible way. Suppose she deviates from announcing Σ_i, which we constructed under full commitment. Then the vetoing firm holds the off-path belief on her being the *high* type. The signal Σ_i satisfies the designer's incentive constraints. □

A.7 Proof of Proposition 5

Proof. The proof is constructive. Take any SSO, say SSO^0, 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 payoff distribution induced by the play of the veto equilibrium. Then, we show that there is an SSO, say SSO^1, which is unanimously accepted and leads to the same payoff distribution.

Firms might randomize their veto decision. Let $\xi(c)$ be the probability that SSO^0 is vetoed given type profile $c := (c_1, c_2)$. Moreover, $\xi_i(c_i)$ is the likelihood that type c_i of firm i vetoes SSO^0 on the equilibrium path. The set of firms that vetoed, V, might be random.[30] After the veto decision, firms observe the set of firms that vetoed, say $\mathcal{V}$, and update to information structure $I^{\mathcal{V}}$, and payoffs realize according to $V_i(c_i|c_i, I^{\mathcal{V}})$. Taking expectations over all possible realizations of the set of vetoing firms, $\mathcal{V}$, the ex-ante expected continuation game conditional on a veto is a lottery $(P(\mathcal{V}), V_i(c_i|c_i, I^{\mathcal{V}}))$ defined over all $\mathcal{V}$. $P(\mathcal{V})$ is the on-path likelihood that a veto is caused by the set $\mathcal{V}$ and not by any other set of vetoing firms. Conditional that no firm vetoes, the information structure is I^a.

Now construct SSO^1. We invoke the revelation principle and assume, without loss of generality, that SSO^1 is a direct revelation mechanism to which firms truthfully report (conditional on acceptance). Its outcome function, i.e., the report-profile dependent distribution over shares and the disagreement outcome is as follows. If both firms accept SSO^1, then it replicates the lottery over payoffs that is induced in the equilibrium of the above described veto grand game (where the SSO was SSO^0).

We now construct a signaling device Σ such that SSO^1 is implementable under full participation. By construction, SSO^1 is incentive compatible. What remains is to show that no firm has an incentive to veto SSO^1.

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

No firm i has an incentive to veto the SSO. If a firm vetoes the SSO the signals Σ_i provide the firm with the same lottery over information structures that it 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 SSO^1.

Finally, truthful reporting to Σ_i is a best response as Σ_i is payoff irrelevant on the equilibrium path. Thus, under (SSO^1, Σ) an equilibrium with full participation in SSO^1 exists that implements the same outcome as the veto equilibrium. $\square$

[30] I.e., if firm i vetoes then this set realizes as either $\{i\}$ or as $\{i, -i\}$

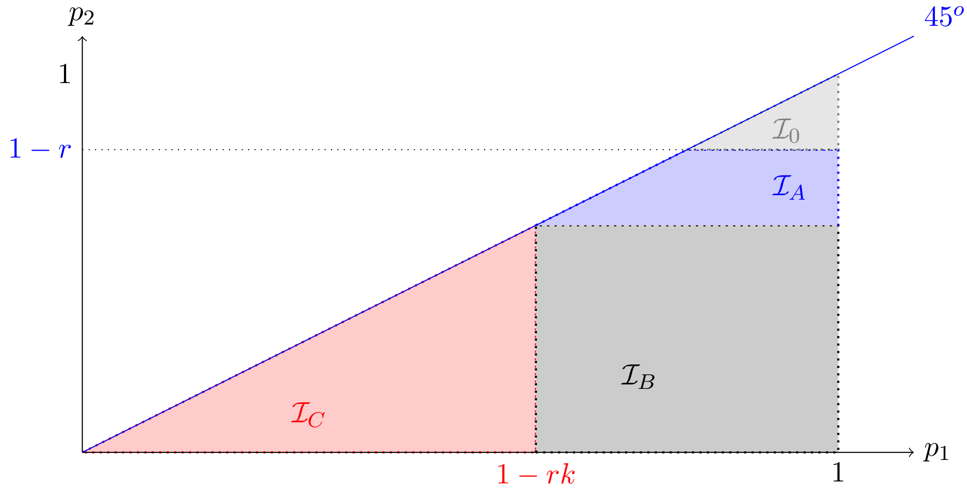


Figure 6: Partitioning the information set, given $p_1 \geq p_2$. Each partition corresponds to a type of equilibrium. See Lemma 1 for an analytical description.

B Proof of Lemma 1

Outline. We solve the 2-player standard war for a general information structure. Lemma 1 is a corollary to Lemma 5. Lemma 5 in turn is a corollary to Siegel (2014). We state the arguments for completeness below in appendix B.2.

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

We first characterize the firm's equilibrium strategies which imply the equilibrium payoffs. We assume throughout wlog that $p_1 \geq p_2$.

An information structure in the general framework is $I = (p_1, p_2)$, I can be in one of 4 sets. Figure 6 depicts the regions in the (p_1, p_2) plane

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

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 5. 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

$$
\begin{aligned}
V_i(1) &= 1 - r - p_2, \\
V_i(k) &= 0.
\end{aligned}
$$

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

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

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

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

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

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

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

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

$$V_2(c_h) = 0.$$

Proof. The equilibrium construction in each case follows 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. All equilibria are payoff equivalent.[31]

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

$$\frac{\partial Pr(e_i > e_{-i}|s_{-i}, I)}{\partial e_i} - c_i = 0.$$

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

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

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

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

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

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

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

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

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

[31] See below for the respective argument.

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: $I\in\mathcal{I}_C$

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

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

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

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

Player 1, type 1 receives payoff

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

from investing Δ_1, which is the same when investing until the top of its specified interval.

Player 2, type 1 receives payoff

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

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

□

B.2 Adaptation of the Siegel (2014) framework

Outline. 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 regimes.

Lemma 6 (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 6 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 regimes. Take regime $\mathcal{I}^0$, 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 6 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 regime $\mathcal{I}^A$ we have that $r < 1 - p_2$. Firm 2 type 1 invests on the interval $(r, \overline{e}]$ for some $\overline{e} < 1$. At the same time $r > (1 - p_2)/k$ such that firm 2 type k can be successfully deterred. Only type-1 cost firms invest a positive amount and firm 1 uses its residual mass for investment at r, it wins with the likelihood that firm 2 is the k-cost type. Both type-1 cost firms make (the same) positive profits, type-k cost firms make no profit.

In regime $\mathcal{I}^B$ 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 regime $\mathcal{I}^C$, firm 2's incentives to participate increase (compared to regime $\mathcal{I}^B$) 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.

B.3 Tullock Contest

Here we show that our findings extend to Tullock contests. We use the same model as in the main text yet with a Tullock contest and without a reserve price (or a sufficiently low reserve price) for tractability.

Contest Success Function. In a Tullock contest winning the standard war is random, even conditional on the firms' investment levels. Assume that there is no reserve price, $r = 0$. Let $e_{-i}(c_{-i}; (1, p_{-i}))$ be firm $-i$'s equilibrium investment when firm $-i$ is equipped with cost c_{-i} and the information structure is $I = (1, p_{-i})$. Consider the case in which all types invest a positive amount in equilibrium ($\Leftrightarrow k \leq 4$) regardless of the type distribution. To shorten notation let $\underline{e} := e_{-i}(k; (1, p_{-i}))$ and $\overline{e} := e_{-i}(1; (1, p_{-i}))$. Firm i's problem becomes

$$\max_{e_i} p_{-i} \frac{e_i}{e_i + \overline{e}} + (1 - p_{-i}) \frac{e_i}{e_i + \underline{e}} - e_i,$$

whereas firm $-i$ faces the problem

$$\max_{e_{-i}} \frac{e_{-i}}{e_{-i} + e_i^*} - c_i e_{-i},$$

where e_i^* is firm i's optimal effort selection. Following, e.g., Denter, Morgan, and Sisak (2021) or Zhang and Zhou (2016) we can derive the optimal effort levels in that case:

$$e_i^* = \left(\frac{p_{-i} + (1 - p_{-i})\sqrt{k}}{1 + p_{-i} + (1 - p_{-i})k} \right)^2,$$

$$\overline{e} = \sqrt{e_i^*} - e_i^*,$$

$$\underline{e} = \sqrt{e_i^*/k} - e_i^*.$$

Plugging them into i's payoffs delivers

$$v_i(1;p_{-i}) = p_{-i}\frac{e_i^*}{e_i^* + \overline{e}} + (1-p_{-i})\frac{e_i^*}{e_i^* + \underline{e}} - e_i^*.$$

Informational Punishment. Deriving general conditions is difficult as $v_i(1;p_{-i})$ is a complicated object to analyze. However, if we restrict attention to the case in which $k = 4$ the expected payoff for the vetoing firm i is

$$v_i(1;p_{-i}) = \frac{(4-3p_{-i})(2-p_{-i})^2}{(5-3p_{-i})^2},$$

with second derivative

$$\frac{\partial^2}{\partial p_{-i}\partial p_{-i}} v_i(1;p_{-i}) = 2\frac{(3p_{-i}-8)}{(3p_{-i}-5)^4} < 0.$$

Thus, the vetoer's payoff is concave in p_{-i} which implies that informational punishment is beneficial. For concreteness consider the case in which $p_1 = p_2 = p = 9/25$. Then a standard war is inevitable without informational punishment because

$$v_i(1;9/25) = 122713/240100 \approx 0.51 > 1/2.$$

Now consider informational punishment that fully discloses types. That implies that we obtain

$$\begin{aligned} v_i(1;0) &= 16/25, \\ v_i(1;1) &= 1/4, \\ \rho(\sigma_{-i} = l) &= p. \end{aligned}$$

But then coordination is possible because

$$v(1;\Sigma^*) = 9/25\ v_i(1;1) + 14/25\ v_i(1;0) = 1121/2500 \approx 0.45 < 1/2.$$

Thus, in a lottery contest informational punishment can be beneficial even absent a minimum investment.[32]

B.4 Tournaments

Here we show our findings are robust to an alternative specification in which we consider the standard war as a torunament.

[32] In fact, concavity of $v_i(1;p_{-i})$ is not unique to our chosen specification but (at least numerically) robust to other values of k provided we have an interior solution. We conjecture that if the high-cost type stays out of the competition for some values of p_{-i} (which happens when $k > 4$) the effect becomes even stronger for the same reasons as in the frictionless contest from the main text.

As before, there are two firms. In the standard war they play a (Lazear and Rosen (1981)-inspired) tournament. Each firm select an investment level $e_i \in [0,1]$ that translates to an output $q_i = e_i + \varepsilon_i(c_i)$, where ε is 'noise'—a random variable that depends on the type c_i. Firm $-i$ wins the standard what if $q_{-i} \geq q_i \Leftrightarrow (e_{-i} - e_i) \geq \varepsilon_i(c_i) - \varepsilon_{-i}(c_{-i})$.

To ensure an interior solution, we assume that cost of effort are identical and quadratic, $\eta e_i^2/2$. Moreover, as before we restrict attention to firm i being type $c_i = 1$, firm 2 can has different types $c_{-i} = \{1, k\}$ distributed according to p_{-i}. Define $\Delta^{c_{-i}} := \varepsilon_i(1) - \varepsilon_{-i}(c_{-i})$ with $c_{-i} \in \{1, k\}$, which itself is a random variable. To keep the algebra straightforward we make distributional assumptions directly on $\Delta(c_{-i})$. We assume the atomless support of Δ is the same for both types and given by $[-1, 1]$. The distribution is given by $F_{c_{-i}}(\delta)$.

Assume Firm i's decision is e_i^*. Then firm $-i$ solves

$$\max_{e_{-i}} F_{c_{-i}}(e_{-i} - e_i^*)) - \eta \frac{e_{-i}^2}{2},$$

Likewise assume that firm $-i$, type 1 (k) selects $\overline{e}$ ($\underline{e}$. Then, firm i solves

$$\max_{e_i} p(1 - F_1(\overline{e} - e_i)) + (1-p)(1 - F_k(\underline{e} - e_i)) - \eta \frac{e_i^2}{2}.$$

First-order conditions are

$$\begin{aligned} f_1(\overline{e} - e_i) &= \eta \overline{e}, \\ f_k(\underline{e} - e_i) &= \eta \underline{e}, \\ p f_1(\overline{e} - e_i) + (1-p) f_k(\underline{e} - e_i) &= \eta e_i^*. \end{aligned}$$

That implies

$$e_i^* = p\overline{e} + (1-p)\underline{e},$$

and thus

$$f_1\Big((1-p)(\overline{e} - \underline{e})\Big) = \eta \overline{e}, \qquad f_k\Big(p(\underline{e} - \overline{e})\Big) = \eta \underline{e}.$$

Assuming $f_1(x) = (x+1)/2$ (i.e. uniform) and $f_k(x) = ((x+1)/2)^2$ (i.e. linearly increasing) for the densities and $\eta \geq 1 + 1/\sqrt{2}$ to ensure an interior solution we obtain

$$\overline{e} = 1/(2\eta), \qquad \underline{e} = \frac{(2\eta - p)}{2\eta(\eta - p)}, \qquad e_i^* = \frac{\eta + 1}{2\eta} + \frac{\eta - 1}{2(p - \eta)}.$$

which implies $\underline{e} - \overline{e} = 1/(2(\eta - p)$ and thus

$$F_1(\overline{e} - e_i^*) = 1/2 - \frac{1-p}{2(\eta - p)}, \qquad F_k(\underline{e} - e_i^*) = \left(1/2 + \frac{p}{2(\eta - p)}\right)^2$$

The payoff for firm i becomes

$$p/2 + \frac{p(1-p)}{2(\eta - p)} + (1-p)\left(1 - \left(1/2 + \frac{p}{2(\eta - p)}\right)^2\right) - \eta\left(\frac{\eta+1}{2\eta} + \frac{\eta - 1}{2(p-\eta)}\right)^2,$$

which to me looks very convex...

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