

# Repeated Coordination with Private Learning<sup>\*</sup>

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## Abstract

We study a repeated game with payoff externalities and observable actions where two players receive information over time about an underlying payoff-relevant state, and strategically coordinate their actions. Players learn about the true state from private signals, as well as the actions of others. They commonly learn the true state (Cripps *et al.*, 2008), but do not coordinate in every equilibrium. We show that it is possible to construct equilibria in which players eventually coordinate on the correct action, for any discount factor. For high discount factors we show that in addition players can also achieve efficient payoffs.

Keywords: repeated games, coordination, learning.

## 1 Introduction

We consider a repeated coordination game with observable actions and with unobserved stage utilities that depend on an unknown, unchanging state of nature. The state is either high ( $H$ ) or low ( $L$ ). In each period, players choose between two actions: invest ( $I$ ) or not invest ( $N$ ). Not investing is a safe action that always yields stage utility 0, whereas investment involves a cost. Investment yields a profit only if the state is high and the other player also invests.

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In each period, each player observes a private signal regarding the state, and chooses whether to invest or not. These signals are independent, and are observed regardless of the actions taken by the players. Thus, for each player the uncertainty regarding the state eventually vanishes, through the aggregation of these signals. However, because signals are private, a player does not know what information the other player has, and hence does not know exactly what his beliefs are. The question that now arises is: can the players coordinate on the right action? That is, can they eventually coordinate on investment when the state is high, and on not investing when the state is low? While common learning (Cripps et al., 2008)—whose introduction was motivated by games of this nature—is obtained in this game, it is far from obvious that coordination is possible.

In the one-shot version of our game, when signals are strong enough, players can coordinate on the correct action, with high probability; this follows from known results on common- $q$  beliefs in static Bayesian games (Monderer and Samet, 1989). In our repeated setting, since signals accumulate over time, private information does indeed become strong. However, because agents are forward looking, the situation is much more complicated, and it becomes unclear if coordination is still possible. Another complication stems from the fact that a player's beliefs are influenced both by his own private signals, as well as the actions of the other player. Thus reasoning directly about players' beliefs is impossible, and one needs to revert to more abstract arguments, in the flavor of the social learning literature, in order to analyze the dynamics. Indeed, the question that we ask regarding eventual coordination on the correct action closely corresponds to key questions regarding eventual learning addressed in the social learning literature (e.g., Smith and Sørensen, 2000).

We show that it is indeed possible to coordinate with high probability. In fact, we construct equilibria with the stronger property of *action efficiency*, in which, from some time period on, the players only choose the correct action. We further show that these equilibria achieve near optimal *payoff efficiency* when the discount factor is high.

Static coordination games of this kind have become an insightful way to model many real-world problems such as currency attacks (Morris and Shin, 1998), bank runs (Goldstein and Pauzner, 2005), political regime changes (Edmond, 2013), and arms races (Baliga and Sjöström, 2004). Yang (2015) considers investment in a fluctuating risky asset, where the payoff depends, as in our paper, on both the fundamentals (the state of nature) and the action of the other player. A common assumption in this literature is that direct communication is not allowed. We also make this assumption, and indeed our question is trivial without it.

We describe both equilibrium strategies and payoffs. The construction of the equilib-

rium is not fully explicit; at some point we have to use a fixed point theorem to show existence of the equilibria with the properties we desire.

The construction is roughly as follows: Initially, players play action  $N$  for a sufficiently long amount of time, enough to accumulate a strong private signal. After this, an *investment phase* begins, in which players invest if their beliefs are above some threshold level. In the high state, both players are very likely to be above this threshold, while in the low state they are both likely to be below it.

The investment phase continues until one (or both) of the players choose  $N$ , in which case a *cool-off phase* of predetermined length is triggered. During the cool-off phase the players do not invest, and instead again accumulate signals, so that, at the end of the the cool-off phase and the beginning of the next investment phase, they are again likely to choose the correct action.

In the high state, we show that each investment phase can, with high probability, last forever. Indeed, we show that almost surely, eventually one of these investment phases will last forever, and so the players eventually coordinate on the correct action. In the low state, we show that eventually players will stop investing, as their beliefs become too low to ever pass the investment thresholds. Thus, almost surely, our equilibria display *action efficiency*, with the players coordinating on the right action.

Action efficiency is achievable for any discount factor. However, because of the initial phase in which players do not invest, there is a significant loss in payoff for low discount factors. For high discount factors, we show that there is almost no loss in payoff, as compared to agents who start the game knowing the state, and coordinate efficiently.

To prove the existence of our equilibria, we first restrict the players to strategies that implement the above described cool-off and investment phases, and apply a standard fixed point theorem to find an equilibrium in the restricted game. We then show that equilibria of the restricted game are also equilibria of the unrestricted game.

We shall now consider briefly some relevant literature. In Section 2, we formally describe the model. Section 3 contains the analysis and construction of the equilibrium. Section 4 discusses specific aspects of the model in greater detail and Section 5 concludes. Proofs are relegated to the Appendix unless otherwise mentioned.

## Related literature

There is work related to this paper in three different parts of the economics literature.

A very similar setting of a repeated coordination game with private signals regarding a state of nature is offered as a motivating example by [Cripps et al. \(2008\)](#), who develop

the notion of *common learning* to tackle this class of repeated games. We believe that the techniques we develop to solve our game should be easily applicable to theirs.

The literature on *static coordination with private information* mentioned earlier in the introduction has dynamic extensions. The dynamic game of regime change by [Angeletos et al. \(2007\)](#), for example, has a similar set-up in terms of private signals and publicly observable (in aggregate) actions, in a repeated game with a continuum of agents. In their setting, the game ends once the agents coordinate on a regime change. In contrast, in our setting one period of successful investment does not end the game. [Chassang \(2010\)](#) is also related, but differs from our setting in that it has a state of nature that changes over time, and an action that is irreversible.

The recent literature on *folk theorems* in repeated settings is possibly the closest, in its statement of the problem addressed, to our paper. The papers we consider in some detail below are [Yamamoto \(2011\)](#) and [Sugaya and Yamamoto \(2013\)](#). Most of the other existing work on learning in repeated games assumes that players observe public signals about the state, and focuses on equilibrium strategies in which players ignore private signals and learn only from public signals ([Wiseman, 2005, 2012](#); [Fudenberg and Yamamoto, 2010, 2011](#)).

[Yamamoto \(2011\)](#) and [Sugaya and Yamamoto \(2013\)](#) are the closest papers to ours. However, these papers are significantly different along the following dimensions. First, they focus on ex-post equilibria, which are defined as sequential equilibria in the infinitely repeated game in which the state  $\theta$  is common knowledge for each  $\theta$ . Since an ex-post equilibrium is a stronger notion, their folk theorem (based on ex-post equilibria) implies the folk theorem based on sequential equilibria. Their results do not apply to our setting, since they make assumptions that our model does not satisfy. Second, for their folk theorem, they assume that the set of feasible and individually rational payoffs has the dimension equal to the number of players for *every* state. However, this assumption fails to hold in our environment. Third, their folk theorem fails to hold when there are two players and private signals are conditionally independent. Since our work considers such cases, it is complementary to theirs also in this sense.

## 2 Model

We consider an infinitely repeated game of incomplete information. There is an unknown payoff-relevant binary state of nature  $\theta \in \Theta = \{H, L\}$ . Time is discrete and the horizon is infinite, i.e.,  $t = 1, 2, 3, \dots$ . There are two players  $\mathcal{N} = \{1, 2\}$ . Each player  $i$ , at every period  $t$ , chooses an action  $a_i \in A_i = \{I, N\}$ . Action  $I$  can be interpreted as an action to *invest*

and action  $N$  as *not invest*. We assume that the state of nature is determined at period  $t = 1$  and stays fixed for the rest of the game. Further, both players hold a common prior  $(p_0, 1 - p_0) \in \Delta(\Theta)$ , where  $p_0 \in (0, 1)$  is the initial probability that the state is  $\theta = H$ . The payoff to player  $i$ , in every period, from any action profile  $a \in A = A_1 \times A_2$  depends on the state and is defined by a per-period payoff function  $u_i(a, \theta)$ . The following table shows the payoffs from actions associated with states  $\theta = H$  and  $\theta = L$  respectively:

	$I$	$N$
$I$	$1 - c, 1 - c$	$-c, 0$
$N$	$0, -c$	$0, 0$

Table 1:  $\theta = H$

	$I$	$N$
$I$	$-c, -c$	$-c, 0$
$N$	$0, -c$	$0, 0$

Table 2:  $\theta = L$

Here  $c \in (0, 1)$  is a cost of investing, and so investment is beneficial if and only if the other player chooses to invest and the state is  $H$ . In this case both players obtain a payoff equal to  $1 - c$ . In the state  $H$ , there are two stage-game equilibria in pure strategies,  $(I, I)$  and  $(N, N)$ , where the former is Pareto dominant. In the state  $L$ , however, action  $N$  is strictly dominant, thereby the unique stage-game equilibrium being  $(N, N)$ . We assume that stage utilities are not observed by the agents.

**Private Signals.** At every period  $t$ , each player  $i$  receives a *private signal*  $x_{it} \in X$  about the state, where  $X$  is a finite signal space.<sup>1</sup> The signal distribution under the state  $\theta$  is given by  $f_\theta \in \Delta(X)$ . We assume that conditional on the state  $\theta$ , private signals are *independent* across players and across time. We also assume that  $f_H \neq f_L$ . This allows both players to individually learn the state of the nature asymptotically via their own private signals. Finally, we assume full support:  $f_\theta(x) > 0$  for all  $\theta \in \Theta$  and for all  $x \in X$ . Hence, no private signal fully reveals the state of nature.

**Histories and Strategies.** At every period  $t$ , each player  $i$  receives a private signals  $x_{it}$  and then chooses action  $a_{it}$ . Under our assumption of perfect monitoring of actions, player  $i$ 's *private history* before taking an action  $a_{it}$  at period  $t$  is hence  $h_{it} = (a^{t-1}, x_i^t)$ , where we denote by  $a^{t-1} = (a_1, a_2, \dots, a_{t-1}) \in A^{t-1}$  the past action profiles and by  $x_i^t = (x_{i1}, x_{i2}, \dots, x_{it}) \in X^t$  player  $i$ 's private signals. Let  $H_{it} = A^{t-1} \times X^t$  be the set of all period- $t$  private histories for player  $i$ . Note that action history  $a^{t-1}$  is publicly known. Figure 1 depicts the sequence of events. A *strategy* for player  $i$  is a function  $\sigma_i : \bigcup_t H_{it} \rightarrow \Delta(A_i)$ . Let  $\Sigma_i$  denote the set of all player  $i$ 's strategies.

<sup>1</sup>The assumption that the signal space is finite is not crucial for establishing our results. The key feature of the signal distributions that we exploit is that they generate bounded likelihood ratios.

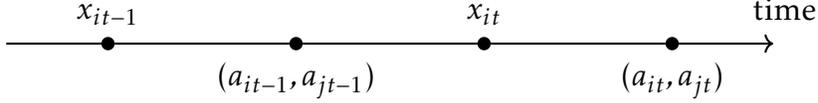


Figure 1: Timeline

**Payoffs.** Both players evaluate infinite streams of payoffs via discounted sum where the discount factor is  $\delta \in (0, 1)$ . Hence, in the infinitely repeated game, if the players choose a path of actions  $(a_t)_{t \in \mathbb{N}} \in A^\infty$ , then player  $i$  receives long-run payoff  $\sum_{t \geq 1} (1 - \delta) \delta^{t-1} u_i(a_t, \theta)$  when the state is  $\theta$ . Hence, under a strategy profile  $\sigma$ , the long-run expected payoff to the player is

$$\mathbb{E}_\sigma \left[ \sum_{t \geq 1} (1 - \delta) \delta^{t-1} u_i(a_t, \theta) \right] \quad (1)$$

where the expectation operator,  $\mathbb{E}_\sigma$ , is defined with respect to the probability measure induced by the strategy profile  $\sigma$  on all possible paths of the repeated interaction  $\Omega = \Theta \times (X^2)^\infty \times A^\infty$ .

**Equilibrium.** For a given strategy profile  $\sigma = (\sigma_i, \sigma_j)$ , we define *continuation values* as  $V_i^\theta(\sigma | h_t)$  for each  $h_t = (a^{t-1}, x_i^t, x_j^t) = (h_{it}, h_{jt})$ . This value represents the long-run expected payoff player  $i$  would obtain at history  $h_t$ , if players play according to the strategies  $\sigma$  and the state is  $\theta$ . At period  $t$ , depending on the private history, player  $i$  has beliefs about the state of nature and private signals of his opponent  $(\theta, x^t) \in \Theta \times X^t$ . Player  $i$ 's *belief function* is given by  $\mu_i : \bigcup_t H_{it} \rightarrow \Delta(\Theta \times X^t)$ . An *assessment* is a pair  $\langle \sigma, \mu \rangle$  consisting of a strategy profile and belief function for each player. We use sequential equilibrium as our solution concept, which we define in the current setting as follows:

**Definition 1.** An assessment  $\langle \sigma^*, \mu^* \rangle$  is a sequential equilibrium if:

1. (Sequential Rationality) The strategy profile  $\sigma^*$  is sequentially rational for each player given beliefs  $\mu^*$ . This means, for each  $h_{it} = (a^{t-1}, x_i^t) \in H_{it}$  and  $\sigma_i \in \Sigma_i$ ,

$$\sum_{(\theta, x_j^t)} \mu_i^*(h_{it})(\theta, x_j^t) V_i^\theta(\sigma^* | a^{t-1}, x_i^t, x_j^t) \geq \sum_{(\theta, x_j^t)} \mu_i^*(h_{it})(\theta, x_j^t) V_i^\theta(\sigma_i, \sigma_{-i}^* | a^{t-1}, x_i^t, x_j^t). \quad (2)$$

2. (Consistency) There exists a sequence of profiles of completely mixed strategies (that assigns positive probability to all actions at all private histories)  $\{\sigma^n\}_{n \geq 1}$  such that the

belief functions  $\{\mu^n\}_{n \geq 1}$  uniquely induced by them satisfy

$$\lim_{n \rightarrow \infty} (\mu_i^n(h_{it}), \sigma_i^n(h_{it})) = (\mu_i^*(h_{it}), \sigma_i^*(h_{it})) \quad (3)$$

for all  $h_{it} \in H_{it}$ , and convergence is with respect to the product topology on  $\Delta(\Theta \times X^t) \times A_i$ .

The definition of sequential equilibrium is borrowed from [Kreps and Wilson \(1982\)](#) and is adapted to our setting. While their definition corresponds to finite extensive-form games, the extension to the current setting is justified since there are only countably many information sets for each player and moreover, each information set is finite.

The following Lemma reduces the problem of finding a sequential equilibrium to that of finding a Nash equilibrium.

**Lemma 1.** *For every Nash equilibrium  $\sigma^*$  in our game there exists an outcome equivalent sequential equilibrium  $(\sigma^{**}, \mu^*)$ .*

### 3 Equilibrium Analysis

In this section, we study equilibria of the infinitely repeated game. Our goal is to establish the existence of equilibria that are efficient. We shall consider two notions of efficiency, namely *action* efficiency and *payoff* efficiency. Action efficiency requires that player actions converge almost surely to the correct actions, i.e., both players eventually invest (resp. not invest) under state  $\theta = H$  (resp.  $\theta = L$ ). Payoff efficiency requires that players obtain payoffs close to efficient payoffs, i.e., in state  $\theta = H$  (resp.  $\theta = L$ ), ex-ante long run payoffs of both players are close to  $1 - c$  (resp. close to 0). The main result is that action efficiency can always be obtained in equilibrium and payoff efficient equilibria exist for discount factor  $\delta$  close to one.

#### One-period Example

To informally illustrate the nature of incentives that arise in our coordination framework, we first consider the scenario when there is only a single period of interaction. Suppose that players follow a threshold rule to coordinate on actions. That is, for each player  $i$ , there exists a threshold belief  $\bar{p}_i$  such that player  $i$  invests (does not invest) if his belief about the state  $\theta = H$  is above (below) the threshold. For simplicity, let us further assume that no posterior belief after the one period signal equals the threshold. Now, if player  $i$ 's

belief  $p_i$  is above his threshold and he chooses to invest, then he obtains a payoff equal to

$$p_i \mathbb{P}[p_j > \bar{p}_j \mid \theta = H] - c,$$

where  $\mathbb{P}[p_j > \bar{p}_j \mid \theta = H]$  is the probability that player  $j$  invests conditional on the state  $\theta = H$ . Since player  $i$  obtains payoff of 0 from not investing, he has an incentive to invest only if this probability is high enough. Moreover, even if it were the case that the other player invests for sure in the state  $H$ , player  $i$  would still need his belief  $p_i$  to be above  $c$  in order to find investment optimal. Hence, when player  $j$  invests with high probability in the state  $H$ , the threshold of player  $i$  would be close to  $c$ . Likewise, if player  $j$  invests with low probability in the state  $H$ , the threshold would be close to one. There may hence arise multiple equilibria. There could be an equilibrium with low thresholds where both players invest with high probability in the state  $H$ . There could also be an equilibrium with high thresholds where this probability is low or even zero.<sup>2</sup>

Note the roles played by both a player's belief about the state, and by his belief about his opponent's beliefs. If player  $i$  believes that the state is  $\theta = H$  with probability 1, his payoff from investing is  $\mathbb{P}[p_j > \bar{p}_j \mid \theta = H] - c$ . Thus, he invests only if he believes that player  $j$  invests with probability at least  $c$ . On the other hand, if he believes that player  $j$  chooses to invest with probability 1, his payoff from investing is  $p_i - c$ . Thus, he invests only if he believes that the state is  $\theta = H$  with probability at least  $c$ . This demonstrates that not only do players need high enough beliefs about the state  $H$  in order to invest, but also need to believe with high probability that their opponents hold high beliefs as well. Both players invest only if they acquire "approximate common knowledge" of the state being  $\theta = H$  (Monderer and Samet, 1989). This naturally raises the question of whether an analogue of this insight obtains in the repeated game we consider here.

Now, imagine that the first period signals were informationally very precise. This would allow a very high probability of investment in the state  $H$  in the low threshold equilibrium. This suggests that if such precise signals were the result of accumulating a series of less precise ones, say received over time, the probability of coordinating on the right actions would be very high. In the infinitely repeated game, such a situation can arise, for example, when players choose to not invest and individually accumulate their private signals, followed by an attempt to coordinate with a low threshold.

In the dynamic context, because players are forward looking, such a threshold rule would also depend on how players behave in the future. For example, if non-investment

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<sup>2</sup>This multiplicity arises from the assumption that investment cannot be strictly dominant in either state, unlike global games (Carlsson and Van Damme, 1993).

triggers both players to not invest forever, the thresholds for investment would be low. This is because non-investment would yield a payoff of 0 whereas investment would yield expected payoff for the current period and a non-negative future continuation payoff (because a player can always guarantee himself a payoff of 0 by never investing on his own).<sup>3</sup> However, having non-investment trigger players not investing forever is not compatible with action efficiency, which requires the players to invest eventually in the high state. Thus action efficient equilibria must somehow incentivize players to revert back to investing.

### 3.1 Cool-off Strategies

We will focus on a particular class of strategies which we call *cool-off strategies*, in which play involves two kinds of phases: *cool-off phases* and *investment phases*. In a cool-off phase, both players accumulate private signals while playing action profile  $(N, N)$  for a certain period of time. After the cool-off phase, they enter an investment phase in which each player chooses action  $I$  with positive probability. In an investment phase, if the players' play action profile  $(I, I)$  then they remain in the investment phase, otherwise they restart a new cool-off phase.

Cool-off strategies are based on the notion of a *cool-off scheme*, which is defined as a partition  $(\mathcal{C}, \mathcal{I})$  of the set of all action histories: the set of cool-off histories  $\mathcal{C}$  and the set of investment histories  $\mathcal{I}$ . This classification is carried out by means of a *cool-off function*  $T : \mathbb{N} \rightarrow \mathbb{N}$  which labels each action history  $a^t$  as being part of a cool-off phase or not. Formally, this is done as follows.

**Definition 2.** A cool-off scheme  $(\mathcal{C}, \mathcal{I})$  induced by a cool-off function  $T : \mathbb{N} \rightarrow \mathbb{N}$  is recursively defined as follows:

1. The empty action history is in  $\mathcal{C}$ .
2. For an action history  $a^t$  such that  $t \geq 1$ :
  - (a) Suppose that  $a^{t-1} \in \mathcal{I}$ . Then,  $a^t \in \mathcal{I}$  if  $a_t = (I, I)$  and  $a^t \in \mathcal{C}$  otherwise.
  - (b) Suppose that  $a^{t-1} \in \mathcal{C}$  and that there exists a subhistory of  $a^t$  in  $\mathcal{I}$ . Let  $a^{s-1}$  be the longest such subhistory. Then,  $a^t \in \mathcal{C}$  if  $t \leq s + T(s) - 1$  and  $a^t \in \mathcal{I}$  if  $t > s + T(s) - 1$ .
  - (c) Suppose that  $a^{t-1} \in \mathcal{C}$  and that there does not exist a subhistory of  $a^t$  in  $\mathcal{I}$ . Then,  $a^t \in \mathcal{C}$  if  $t \leq T(1)$  and  $a^t \in \mathcal{I}$  if  $t > T(1)$ .

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<sup>3</sup>In the model of [Angeletos et al. \(2007\)](#), once sufficiently many players invest (or attack a status quo), they receive payoffs and the game ends. Hence, the issue of "repeated" coordination studied here does not arise in their work.

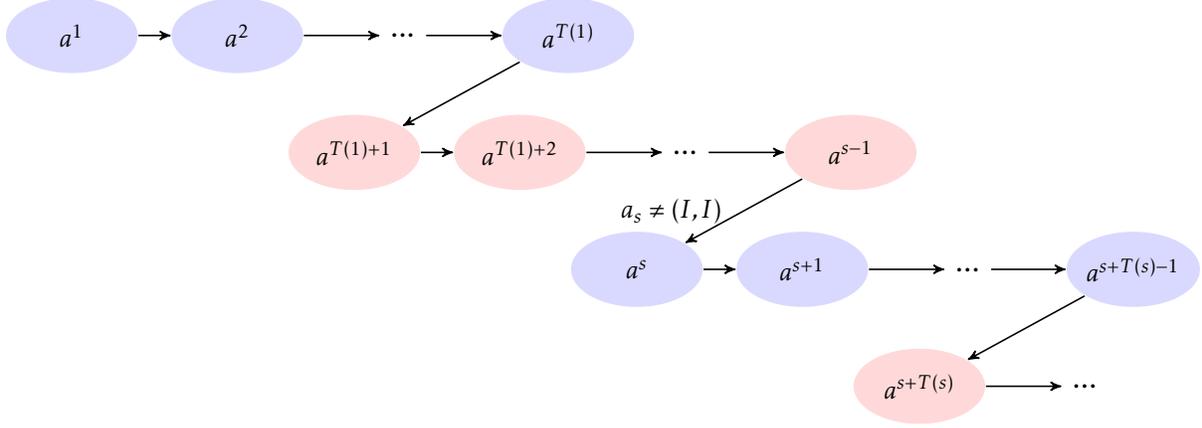


Figure 2: Cool-off Schemes

Each series of action histories in the sets  $\mathcal{C}$  and  $\mathcal{I}$  is called a cool-off phase and an investment phase respectively.

Figure 2 depicts a cool-off scheme. Initially, players are in a cool-off phase for  $T(1)$  periods. At period  $T(1) + 1$ , they are in the investment phase. If both players choose to invest, then they stay in the investment phase. If at some point during the investment phase, say at period  $s$ , at least one player chooses to not invest, then another cool-off phase begins at this action history  $a^s$  for  $T(s)$  periods. Another investment phase starts at period  $s + T(s)$ .<sup>4</sup>

As is clear from Definition 2, the cool-off scheme  $(\mathcal{C}, \mathcal{I})$  induced by any cool-off function  $T$  satisfies both  $\mathcal{C} \cap \mathcal{I} = \emptyset$  and  $\mathcal{C} \cup \mathcal{I} = \bigcup_{t \geq 1} A^t$ . Further, whether an action history  $a^t$  is in a cool-off phase or in an investment phase depends only on the cool-off function  $T$  but not on strategies.

**Definition 3.** Fix a cool-off function  $T$ . We define the set  $\mathcal{S}_i(T)$  as the set of all player  $i$ 's strategies  $\sigma_i \in \Sigma_i$  with the following properties:

1. During a cool-off phase player  $i$  chooses action  $N$  for any realization of their private signals. That is, if  $a^{t-1} \in \mathcal{C}$ , then  $\sigma_i(a^{t-1}, x_i^t) = N$  for any  $x_i^t \in X^t$ .
2. Player  $i$ 's strategy does not depend on the players' actions during the cool-off phase. That is, the strategy  $\sigma_i$  ignores deviations made by any player during the cool-off phase. Hence, if action histories  $a^{t-1}, b^{t-1} \in A^{t-1}$  differ only in cool-off phases, then  $\sigma_i(a^{t-1}, x_i^t) = \sigma_i(b^{t-1}, x_i^t)$  for any  $x_i^t \in X^t$ .

<sup>4</sup>Players may never invest in an investment phase. For example, if action  $a_{T(1)+1} \neq (I, I)$  then this investment phase ends immediately, and a new cool-off phase starts at period  $T(1) + 2$ .

The following claim is immediate.

**Claim 1.** *Fix a cool-off function  $T$ . Then, the set  $\mathcal{S}_i(T)$  is a closed and convex subset of the set  $\Sigma_i$ .*

As stated above, the investment phase corresponds to action histories in which players would invest with positive probability. We have not required that this be the case in Definition 3. For example, the trivial equilibrium, in which both players never invest, belongs to the class  $\mathcal{S}_i(T)$ . Ideally, we would like strategies in the set  $\mathcal{S}_1(T) \times \mathcal{S}_2(T)$  to be such that *whenever* the players are in an investment phase, there is a positive probability of investment. Hence, we focus on the following subclass of strategies.

**Definition 4.** *Fix a cool-off function  $T$  and a constant  $\varepsilon > 0$ . We define the set  $\mathcal{S}_i(T, \varepsilon)$  as the set of all player  $i$ 's cool-off strategies  $\sigma_i$  with the following properties:*

1.  $\sigma_i \in \mathcal{S}_i(T)$ .
2. *In an investment phase, player  $i$  invests with probability at least  $1 - \varepsilon$ , conditioned on the state  $\theta = H$ . That is, for any action history  $a^{t-1} \in \mathcal{I}$ ,*

$$\mathbb{P}_{\sigma_i} [a_{it} = I \mid \theta = H, a^{t-1}] \geq 1 - \varepsilon.$$

Here,  $\mathbb{P}_{\sigma_i} [a_{it} = I \mid \theta = H, a^{t-1}]$  denotes the probability that player  $i$  invests at period  $t$ , given strategy  $\sigma_i$ , conditional on action history  $a^{t-1}$  being reached and the state being  $\theta = H$ . Note that this conditional probability depends on player  $i$ 's strategy but *not* on the strategy specification of player  $j$ . This is because player  $i$ 's strategy at period  $t$ , can be viewed as a map from  $X^t$  to  $\Delta(A_i)$  for each action history  $a^{t-1}$ . Hence, given  $a^{t-1}$ , one can elicit the possible signals  $x_i^t$  that player  $i$  could have potentially received up to period  $t$ . Such an elicitation depends only on player  $i$ 's strategy and solely determines the conditional probability  $\mathbb{P}_{\sigma_i} [a_{it} = I \mid \theta = H, a^{t-1}]$ .

The following claim is again straightforward to prove.

**Claim 2.** *Fix a cool-off function  $T$  and a constant  $\varepsilon > 0$ . Then, the set  $\mathcal{S}_i(T, \varepsilon)$  is a closed and convex subset of the set  $\Sigma_i$ .*

### 3.2 Cool-off Equilibria as Fixed Points

We have introduced the key class of strategies. In what follows, we will find an equilibrium in this class. To do this, we make an appropriate choice of a cool-off function  $T$  and an  $\varepsilon$ , and restrict the players to choose strategies from  $\mathcal{S}_i(T, \varepsilon)$ . Since this set is closed

and convex (Claim 2), we can appeal to a standard fixed point argument to show the existence of an equilibrium. We next show that this equilibrium in restricted strategies is, in fact, still an equilibrium when the restriction is removed. Finally, we show that in this equilibrium, players will eventually coordinate on the right action. Moreover, when the players are very patient, the equilibrium achieves close to efficient payoffs.

**Lemma 2** (Continuation Values). *Let  $\sigma_j$  be any mixed strategy of player  $j$ . Fix an action history  $a^{t-1}$ . Then the continuation value of player  $i$  at the action history  $a^{t-1}$  is a non-decreasing convex function of his belief in the state  $\theta = H$ .*

**Lemma 3** (Threshold Rule). *For each  $c, \delta \in (0, 1)$ , let  $T_0 \in \mathbb{N}$  be large enough and  $\varepsilon > 0$  small enough that*

$$\delta^{T_0} < (1 - \delta)(1 - c - \varepsilon). \quad (4)$$

*Let a cool-off function  $T$  be such that  $T(t) \geq T_0$  for all  $t \geq 2$ . Fix player  $j$ 's strategy  $\sigma_j \in \mathcal{S}_j(T, \varepsilon)$  and an action history  $a^{t-1} \in \mathcal{I}$ . Then, for every best response of player  $i$ , there exists a threshold  $\pi$  such that at action history  $a^{t-1}$  player  $i$  invests (resp. does not invest) if her belief in the state  $\theta = H$  is above (resp. below) the threshold  $\pi$ .*

Lemma 3 implies that for an appropriate choice of  $T$  and  $\varepsilon$ , it holds in every equilibrium of the game restricted to  $\mathcal{S}(T, \varepsilon) = \mathcal{S}_1(T, \varepsilon) \times \mathcal{S}_2(T, \varepsilon)$  that both players play threshold strategies: in each history each player has a threshold such that he invests above it and does not below it. Thus, when a player observes another player investing, he updates upwards (in the sense of stochastic dominance) his belief regarding the other player's signal. A consequence of this is the following corollary, which states this idea formally.

In what follows, we shall denote by  $p_{it}$  the private belief of player  $i$  at period  $t$  before choosing action  $a_{it}$ . The belief  $p_{it}$  is computed based on player  $i$ 's private history  $h_{it} = (a^{t-1}, x_i^t)$ . Hence,  $p_{it} = \mathbb{P}[\theta = H \mid h_{it}]$ .

**Corollary 1** (Monotonicity of Expected Beliefs). *For each  $c, \delta \in (0, 1)$ , let  $T_0 \in \mathbb{N}$  be large enough and  $\varepsilon > 0$  small enough so as to satisfy condition (4) of Lemma 3. Let  $T$  be a cool-off function such that  $T(t) \geq T_0$  for all  $t \geq 2$ . Then, in every equilibrium of the game restricted to  $\mathcal{S}_1(T, \varepsilon) \times \mathcal{S}_2(T, \varepsilon)$  it holds that if  $a^{s-1}$  extends  $a^{t-1}$  with both players investing in periods  $t, t+1, \dots, s-1$ , then*

$$\mathbb{E}[p_{is} \mid \theta = H, a^{s-1}] \geq \mathbb{E}[p_{it} \mid \theta = H, a^{t-1}].$$

**Proposition 1.** For each  $c, \delta \in (0, 1)$ , take  $T_0 \in \mathbb{N}$  large enough and  $\varepsilon > 0$  small enough such that

$$\frac{c}{(1 - \varepsilon) - (1 - c)\delta^{T_0}/(1 - \delta)} < c(1 + 2\varepsilon) < 1 - \varepsilon. \quad (5)$$

Let a cool-off function  $T : \mathbb{N} \rightarrow \mathbb{N}$  be such that  $T(t) \geq T_0$  for all  $t \in \mathbb{N}$ . Fix player  $j$ 's strategy  $\sigma_j \in \mathcal{S}_j(T, \varepsilon)$  and an action history  $a^{t-1} \in \mathcal{I}$ . Then, in every best response of player  $i$ , if

$$\mathbb{E}[p_{it} \mid \theta = H, a^{t-1}] > 1 - \varepsilon^2,$$

then player  $i$  invests with probability at least  $1 - \varepsilon$  in the state  $\theta = H$ . Moreover, player  $i$  invests if his private belief is above  $c(1 + 2\varepsilon)$ .

**Proof.** Denote by  $p$  the supremum of the beliefs in which player  $i$  does not invest at the action history  $a^{t-1}$ . Given the belief  $p$ , the payoff from investing is at least  $(1 - \delta)(-c + p(1 - \varepsilon))$ , while the payoff from not investing is at most  $p\delta^{T_0}(1 - c)$ . Thus, we have that  $(1 - \delta)(-c + p(1 - \varepsilon)) \leq p\delta^{T_0}(1 - c)$ . Rearranging the terms, we have

$$p \leq \frac{c}{(1 - \varepsilon) - (1 - c)\delta^{T_0}/(1 - \delta)},$$

which implies that  $p < c(1 + 2\varepsilon)$  by condition (5). Hence, player  $i$  invests if his private belief  $p_{it}$  is above  $c(1 + 2\varepsilon)$ .

It follows from Markov's inequality that

$$\mathbb{P}(p_{it} \leq p \mid \theta = H, a^{t-1}) = \mathbb{P}(1 - p_{it} \geq 1 - p \mid \theta = H, a^{t-1}) \leq \frac{\mathbb{E}[1 - p_{it} \mid \theta = H, a^{t-1}]}{1 - p}.$$

Since  $p < c(1 + 2\varepsilon)$  and  $\mathbb{E}[p_{it} \mid \theta = H, a^{t-1}] > 1 - \varepsilon^2$ ,

$$\frac{\mathbb{E}[1 - p_{it} \mid \theta = H, a^{t-1}]}{1 - p} < \frac{1 - (1 - \varepsilon^2)}{1 - c(1 + 2\varepsilon)} < \varepsilon,$$

where the latter inequality follows by condition (5). Hence,  $\mathbb{P}(p_{it} \leq p \mid \theta = H, a^{t-1}) \leq \varepsilon$ . That is, player  $i$  invests with probability at least  $1 - \varepsilon$ .  $\blacksquare$

**Proposition 2.** For each  $c, \delta \in (0, 1)$ , let  $T_0 \in \mathbb{N}$  and  $\varepsilon > 0$  be such that condition (4) in Lemma 3 is satisfied. Then, there is a cool-off function  $T : \mathbb{N} \rightarrow \mathbb{N}$  with  $T(t) \geq T_0$  for each  $t \geq 2$  such that, in every equilibrium strategy profile  $\sigma \in \mathcal{S}_1(T, \varepsilon) \times \mathcal{S}_2(T, \varepsilon)$ , it holds in every action history

$a^{t-1} \in \mathcal{I}$  that for each  $i = 1, 2$ ,

$$\mathbb{E}_\sigma[p_{it} \mid \theta = H, a^{t-1}] > 1 - \varepsilon^2.$$

**Proof.** Fix  $T_0 \in \mathbb{N}$  and  $\varepsilon > 0$ . Since private signals are bounded, for each  $s \geq 1$ , there exists  $\underline{p}_s > 0$  such that for each  $i = 1, 2$ ,

$$\mathbb{P}[p_{is} > \underline{p}_s] = 1.$$

irrespective of the strategies of the players. For example,  $\underline{p}_s$  could be defined as the belief that a player would have if he observed both players received the worst signal repeatedly up to period  $s$ , where the worst signal is defined as the one which has the lowest likelihood ratio. Note that  $\underline{p}_s$  only depends on the period  $s$  and not on the action history or the private history of any player.

We now construct the cool-off function  $T$ . For each  $s \geq 1$ , define  $T(s) \geq T_0$  large enough to be such that if a cool-off phase were to begin at period  $s$  and a player's belief were  $\underline{p}_s$ , then when the cool-off phase ends at time period  $s + T(s) - 1$ , the expectation of a player's private belief conditional on  $\theta = H$  would be above  $1 - \varepsilon^2$ .

For this cool-off function  $T$ , from Corollary 1 it follows that for each equilibrium strategy profile  $\sigma \in \mathcal{S}_1(T, \varepsilon) \times \mathcal{S}_2(T, \varepsilon)$  and action history  $a^{t-1} \in \mathcal{I}$ , we have that

$$\mathbb{E}_\sigma[p_{it} \mid \theta = H, a^{t-1}] > 1 - \varepsilon^2,$$

which completes the proof. ■

Now we prove the existence of equilibria in cool-off strategies. Applying a fixed-point theorem to the game restricted to  $\mathcal{S}_1(T, \varepsilon) \times \mathcal{S}_2(T, \varepsilon)$ , we find an equilibrium  $\sigma^* \in \mathcal{S}(T, \varepsilon)$ . We then show that this equilibrium remains an equilibrium of the unrestricted game, using Propositions 1 and 2.

**Proposition 3.** *For each  $c, \delta \in (0, 1)$ , let  $T_0$  be large enough and  $\varepsilon$  small enough so as to satisfy condition (4) in Lemma 3 and condition (5) in Proposition 1. Then, there exists a cool-off function  $T$  with  $T(t) \geq T_0$  for all  $t \geq 2$  and there exists an equilibrium  $\sigma^* = (\sigma_i^*, \sigma_j^*)$  such that  $\sigma_i^* \in \mathcal{S}_i(T, \varepsilon)$  and  $\sigma_j^* \in \mathcal{S}_j(T, \varepsilon)$ .*

### 3.3 Efficiency

**Theorem 1 (Action Efficiency).** *For each  $c, \delta \in (0, 1)$ , there exist a cool-off function  $T$ , a constant  $\varepsilon > 0$  such that for any equilibrium  $\sigma^* \in \mathcal{S}(T, \varepsilon)$ , players eventually choose the right*

actions. That is, the equilibrium action profile converges to  $(I, I)$  in the state  $\theta = H$  and to  $(N, N)$  in the state  $\theta = L$  almost surely.

**Proof.** The underlying probability space for defining the events of interest will be the set of all outcomes  $\Omega = \Theta \times A^\infty \times (X^2)^\infty$ . Let  $\sigma^* \in \mathcal{S}(T, \varepsilon)$  be any equilibrium. Define the events

$$A_I^\infty = \left\{ \omega \in \Omega : \lim_{t \rightarrow \infty} a_t(\omega) = (I, I) \right\}, \quad A_N^\infty = \left\{ \omega \in \Omega : \lim_{t \rightarrow \infty} a_t(\omega) = (N, N) \right\}.$$

We wish to show that  $\mathbb{P}(A_I^\infty \mid \theta = H) = \mathbb{P}(A_N^\infty \mid \theta = L) = 1$ . Consider the latter equality. It would suffice to show that there exists a  $\underline{p} \in (0, 1)$  such that no player invests when his private belief is below  $\underline{p}$ . In the state  $\theta = L$ , players' private beliefs almost surely converge to 0 (since they can learn from their own signals) and hence will eventually fall below  $\underline{p}$ , leading both players to not invest from some point on. We derive such a  $\underline{p}$ .

When a player has belief  $p$ , the payoff from investing is at most  $(1 - \delta)(p - c) + \delta(p(1 - c))$  and the payoff from not investing is at least 0. Hence, if a player finds it optimal to invest at  $p$ , then

$$p \geq \frac{c - c\delta}{1 - c\delta}.$$

Hence, we can define  $\underline{p} = \frac{c - c\delta}{1 - c\delta}$ . It now follows that  $\mathbb{P}(A_N^\infty \mid \theta = L) = 1$ .

We next show  $\mathbb{P}(A_I^\infty \mid \theta = H) = 1$ . Consider the event  $B^\infty = \{\omega \in \Omega : \lim_{t \rightarrow \infty} p_{it}(\omega) = 1 \text{ for both } i = 1, 2\}$ . We know that  $\mathbb{P}(B^\infty \mid \theta = H) = 1$ . Hence, it suffices to show that  $B^\infty \subseteq A_I^\infty$ .

Let  $\omega \in B^\infty$ . It suffices to show that on the outcome path induced by  $\omega$ , there must only be finitely many cool-off periods. Suppose not. Then, there exist infinitely many cool-off periods in  $\omega$ . Recall from Proposition 1 that a player invests with probability one in an investment phase when his private belief is above  $\bar{p} = c(1 + 2\varepsilon)$ . Now, since  $\omega \in B^\infty$ , there exists a  $\bar{T}$  such that  $p_{it}(\omega) > \bar{p}$  for all  $t \geq \bar{T}$  for both  $i = 1, 2$ . Now, let  $t'$  be the starting period of the first cool-off phase after  $\bar{T}$ . Then,  $T(t') + t' \geq \bar{T}$ . Hence, when this cool-off period ends at time  $s = T(t') + t' - 1$ , we enter an investment phase. Since this investment phase at  $s + 1$  starts beyond period  $T'$ , the private beliefs of both players would be above  $\bar{p}$  and both players would invest in time period  $s + 1$ . Next period, players would continue to be in the investment phase and again invest. Proceeding this way, players would keep on investing which means the investment phase would last forever. This contradicts the fact that there are infinitely many cool-off periods. Hence, there exist only finitely many cool-off periods in  $\omega$ , which means that players invest forever after some point of time. Hence,  $\omega \in A_I^\infty$ . ■

**Theorem 2** (Payoff Efficiency). *Fix any  $c \in (0, 1)$ . For every  $\Delta > 0$ , there exists  $\bar{\delta} \in (0, 1)$  such that for each  $\delta \geq \bar{\delta}$ , there exist a cool-off function  $T$ , a constant  $\varepsilon > 0$ , such that in any equilibrium  $\sigma^* \in \mathcal{S}(T, \varepsilon)$ , both players obtain a payoff of at least  $1 - c - \Delta$  in the state  $\theta = H$  and a payoff of at least  $-\Delta$  in the state  $\theta = L$ .*

**Proof.** Fix  $c, \Delta \in (0, 1)$ . Let  $\varepsilon > 0$  be small enough so that  $c < c(1 + 2\varepsilon)(1 - \varepsilon) < (1 - \varepsilon)^2$  and moreover

$$(1 - \varepsilon)^2 \left( \left( 1 - \frac{2\varepsilon}{1 - \bar{p}} \right) (1 - c) + \frac{2\varepsilon}{1 - \bar{p}} (-c) \right) > 1 - c - \Delta. \quad (6)$$

and

$$(1 - \varepsilon) \left( \frac{-\Delta}{2} \right) - \varepsilon c > -\Delta. \quad (7)$$

where recall from Proposition 1 that  $\bar{p} = c(1 + 2\varepsilon)$ . In what follows, we will show that players achieve a payoff equal to the LHS of (6) in state  $\theta = H$  and a payoff equal to the LHS of 7 in state  $\theta = L$ . Let  $T_1 \in \mathbb{N}$  be such that for any strategy profile which implements a cool-off scheme  $T$  with  $T(1) = T_1$ , it holds that i)  $\mathbb{E}[p_{iT_1} \mid \theta = H] > 1 - \varepsilon^2$  for all  $i = 1, 2$ ; ii)  $\mathbb{P}[p_{iT_1} > 1 - \varepsilon \text{ for each } i = 1, 2 \mid \theta = H] > 1 - \varepsilon$ ; iii)  $\mathbb{P}[p_{iT_1} < \frac{\Delta}{2(1-c)+\Delta} \text{ for each } i = 1, 2 \mid \theta = H] > 1 - \varepsilon$ . Now let  $\bar{\delta} \in (0, 1)$  be such that  $(1 - \bar{\delta})\bar{\delta}^{T_1} > 1 - \varepsilon$ . Let  $\delta > \bar{\delta}$ . Now, suppose that  $T_0$  is such that condition (4) in Lemma 3 and condition (5) in Proposition 1 are satisfied for  $T_0$  and  $\varepsilon$ . From Proposition 3, it follows that there exists a cool-off function with  $T(1) = T_1$  and  $T(t) \geq T_0$  for all  $t \geq 2$  and there exists an equilibrium of the repeated game restricted to strategies in  $\mathcal{S}(T, \varepsilon)$ . Let  $\sigma^*$  be one such equilibrium.

We shall show that in this equilibrium each player obtains a long-run expected payoff of at least  $1 - c - \Delta$  in the state  $\theta = H$  and  $-\Delta$  in state  $\theta = L$ . We first establish the former. Note that we have  $1 - \varepsilon > c(1 + 2\varepsilon)$ . Hence, if the private beliefs of both players are above  $1 - \varepsilon$  at the end of the first cool-off phase with length  $T_1$ , and stay above  $1 - \varepsilon$  forever, both players would invest forever. We shall show that the probability with which this happens is at least  $1 - \frac{2\varepsilon}{1 - \bar{p}}$ . We argue as follows. Suppose that private beliefs for players 1 and 2 are  $p_1, p_2 \geq 1 - \varepsilon$  at time  $T_1$ . Hence, from period  $T_1$  onwards, the probability that both players invest forever is at least

$$\mathbb{P}\left[ p_{it} > \bar{p} \text{ for each } i = 1, 2 \text{ and } t \geq T_1 \mid p_{iT_1} = p_i, p_{jT_1} = p_j, \theta = H \right]. \quad (8)$$

Note that conditional on  $p_{iT_1} = p_i, p_{jT_1} = p_j$  and  $\theta = H$ , the belief process  $p_{it}$  is a bounded

submartingale. Now define the stopping time

$$T_i(\omega) = \min\{t \mid p_{it}(\omega) \leq \bar{p}\}.$$

Let  $p'_{it}$  be the process  $p_{it}$  stopped at time  $T_i$ . It follows that  $p'_{it}$  is a bounded submartingale as well. From the Martingale Convergence Theorem, it converges almost surely to a limit  $p'_{i,\infty}$ . Hence, the conditional probability in (8) is at least

$$\mathbb{P}[p'_{i,\infty} > \bar{p} \text{ for each } i = 1, 2 \mid p_{iT_1} = p_i, p_{jT_1} = p_j, \theta = H].$$

From the Optional Stopping Theorem, we have that

$$\mathbb{E}[p'_{i,\infty} \mid p_{iT_1} = p_i, p_{jT_1} = p_j, \theta = H] \geq p_i.$$

Since  $1 - p'_{i,\infty}$  is non-negative and  $p_i \geq 1 - \varepsilon$ , from Markov's inequality it follows that for each  $i$ ,

$$\mathbb{P}[p'_{i,\infty} \leq \bar{p} \mid p_{iT_1} = p_i, p_{jT_1} = p_j, \theta = H] \leq \frac{\varepsilon}{1 - \bar{p}}.$$

From the above we obtain that the probability that both players will invest from period  $T_1$  onwards is at least  $1 - \frac{2\varepsilon}{1 - \bar{p}}$ . Hence, the long-run expected payoff to each player in state  $\theta = H$  will be at least equal to the LHS of (6) which is greater than  $1 - c - \Delta$ .

Finally, we show that under  $\sigma^*$ , the payoff in state  $L$  is at most  $-\Delta$ . To see this, we first make the following observation. Suppose at the end of the first  $T_1$  cool-off periods, a player's private belief is  $p \leq \frac{\Delta}{2(1-c)+\Delta}$ . Now from Lemma 2, we know that a player's optimal continuation value  $v(\cdot)$  is a non-decreasing convex function of his private belief  $p$ . We show that if the optimal continuation strategy of the player yields payoffs  $(v_H, v_L)$  at  $p$ , then  $v_L \geq -\frac{\Delta}{2}$ . Since  $(v_H, v_L)$  is the optimal continuation value at  $p$ , it follows that the vector  $(v_H, v_L)$  supports the convex function  $v(\cdot)$  at  $p$ . Hence,

$$v(p) = pv_H + (1 - p)v_L.$$

Note that  $v(p) \geq 0$  since a player can always guarantee himself a payoff of zero forever and  $v_H \leq 1 - c$  since the best payoff a player can get in state  $H$  is  $1 - c$ . These, together with the fact that  $p \leq \frac{\Delta}{2(1-c)+\Delta}$ , imply  $v_L \geq -\frac{\Delta}{2}$ . Now, since we have  $\mathbb{P}[p_{iT_1} < \frac{\Delta}{2(1-c)+\Delta} \text{ for each } i = 1, 2 \mid \theta = H] > 1 - \varepsilon$ , the ex-ante payoff in state  $L$  to each player is at least equal to the LHS of (7), which is greater than  $-\Delta$ . ■

## 4 Discussion

### 4.1 Ex-post Equilibria

Most of the literature in repeated games assumes that the set of feasible and individually rational payoffs is full-dimensional. That is, the dimension of the set is equal to the number of players. Analogously, existing work in repeated games of incomplete information assumes a version of full-dimensionality, called statewise full-dimensionality (e.g., [Wiseman, 2005, 2012](#); [Yamamoto, 2011](#); [Sugaya and Yamamoto, 2013](#)). However, our payoff structure does not satisfy this condition. In addition, two closely related papers to ours, [Yamamoto \(2011\)](#) and [Sugaya and Yamamoto \(2013\)](#), focus on a special class of sequential equilibria, called ex-post equilibria. Yet, any ex-post equilibrium is inefficient in our model, and this is due to the lack of the statewise full-dimensionality. We discuss each of these two differences in turn.

**Statewise Full-dimensionality.** For each state  $\theta$ , we define the set of feasible set of payoffs by

$$W(\theta) = \text{co} \left( \left\{ v \in \mathbb{R}^2 : \exists a \in A \quad \forall i \in \mathcal{N} \quad u_i(a, \theta) = v_i \right\} \right).$$

Further, we define player  $i$ 's minimax payoff in state  $\theta$  by

$$\underline{w}_i(\theta) = \min_{\alpha_j \in \Delta A_j} \max_{a_i \in A_i} u_i(a_i, \alpha_j, \theta)$$

and the set of all feasible and individually rational payoffs in state  $\theta$  by

$$W^*(\theta) = \left\{ w \in W(\theta) : \forall i \in \mathcal{N} \quad w_i \geq \underline{w}_i(\theta) \right\}.$$

Statewise full-dimensionality is said to be satisfied if the set  $W^*(\theta)$  is of dimension equal to the number of players for each  $\theta$ .<sup>5</sup> The statewise full-dimensionality is assumed in most of the literature of repeated games of incomplete information, but it is not in our model. As drawn in [Figure 3](#), the set  $W^*(H)$  is of dimension 2, but the set  $W^*(L) = \{(0, 0)\}$  is not. Intuitively speaking, this lack of statewise full-dimensionality means that players' incentives, thus behavior, are quite different from state to state. This could make it difficult to design an appropriate punishment scheme that supports cooperation.

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<sup>5</sup>When there is no uncertainty of payoff-relevant states, statewise full-dimensionality is equivalent to the full-dimensionality in the literature of repeated games of complete information.

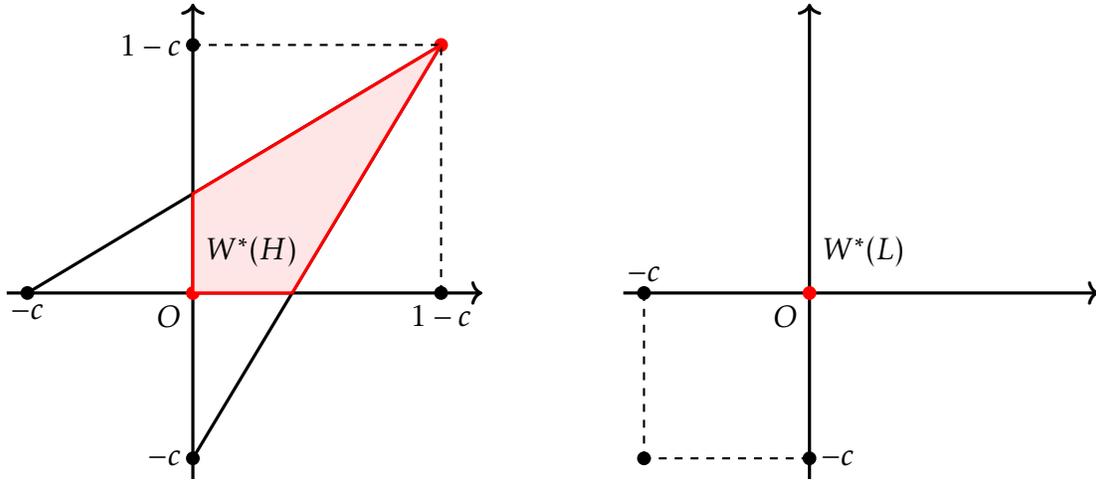


Figure 3: the Lack of Statewise Full-dimensionality

**Ex-post Equilibria.** Two closely related papers to ours, [Yamamoto \(2011\)](#) and [Sugaya and Yamamoto \(2013\)](#), focus on a special class of sequential equilibria, called *ex-post equilibria*. An ex-post equilibrium is defined as a sequential equilibrium in the infinitely repeated game in which the strategies are such that they would be optimal even if the state  $\theta$  were common knowledge. In an ex-post equilibrium, player  $i$ 's continuation play after history  $h_{it}$  is optimal regardless of the state  $\theta$  for each  $h_{it}$  (including off-path histories).

No ex-post equilibrium, however, can approximate efficiency in our model. More precisely, in any ex-post equilibrium, neither player invests at any private history. To see this, note that in any ex-post equilibrium, a player's strategy would be optimal if the state  $L$  were common knowledge. Since in the state  $L$ , a player's best response to any strategy of the opponent is to not invest at any private history, the player never invests even in the state  $H$ . Thus, neither player ever invests in any ex-post equilibrium.

Ex-post equilibria may yield a trivial play if the payoff structure does not satisfy statewise full-dimensionality. Further, they may not exist if a stage game is like a global game. To see this, suppose, for example, that there is another state in which irrespective of the opponent's action, a player gains payoff  $1 - c$  if he invests and payoff of 0 if he does not. Then, players always invest if that state were common knowledge, but they would never invest if the state  $L$  were common knowledge; therefore, there would not exist ex-post equilibria.

## 4.2 Common Learning

A coordination game which is very similar to ours is presented as one of the motivations for the introduction of the concept of common learning by [Cripps et al. \(2008\)](#). We now

explain this concept, and show that, in our game, common learning is attained in every strategy profile.

Recall  $\Omega := \Theta \times A^\infty \times (X^2)^\infty$  is the set of all possible outcomes. Any strategy profile  $\sigma = (\sigma_i, \sigma_j)$  induces a probability measure  $\mathbb{P}$  on  $\Omega$  which is endowed with the  $\sigma$ -algebra  $\mathcal{F}$  generated by cylinder sets. For each  $F \in \mathcal{F}$  and  $q \in (0, 1)$ , define the event  $B_{it}^q(F) = \{\omega \in \Omega : \mathbb{P}(F | a^{t-1}, x_i^t) \geq q\}$ . Now, define the following events:

1.  $B_t^q(F) = B_{it}^q(F) \cap B_{jt}^q(F)$ . That is, this is the event that both players assign probability at least  $q$  to the event  $F$  on the basis of their private information.
2.  $[B_t^q]^n(F) = B_t^q(B_t^q(B_t^q \dots B_t^q(F)))$ . That is, this is the event that both players assign probability at least  $q$  that both players assign probability at least  $q$  that... both players assign probability at least  $q$  to the event  $F$  on the basis of their private information.
3.  $C_t^q(F) = \bigcap_{n \geq 1} [B_t^q]^n(F)$ .

We say that players have *common  $q$ -belief* in event  $F$  at  $\omega$ , at time  $t$ , if  $\omega \in C_t^q(F)$ . We say that players *commonly learn*  $\theta \in \Theta$  if for all  $q \in (0, 1)$ , there exists a  $T$  such that for all  $t \geq T$ ,

$$\mathbb{P}[C_t^q(\theta) | \theta] > q.$$

**Proposition 4.** *Let  $\sigma$  be any strategy profile which induces the probability measure  $\mathbb{P}$ . Then, under  $\mathbb{P}$ , players commonly learn the state  $\theta$  for each  $\theta \in \Theta$ .*

## 5 Conclusion

This paper has attempted to answer the question of whether rational Bayesian players in a coordination game, each of whom is receiving private signals about the unknown state of nature, can both learn to play the action appropriate to the true state and do so in a manner such that the loss in payoffs becomes negligible as the discount factor goes to one. The answer, in a simple setup, is affirmative, even though the particular coordination game we consider does not have properties such as statewise full dimensionality. Future research can be considered along several dimensions. The obvious extension, which is most likely straightforward, would be to have an arbitrary finite number of players and states of nature. A more interesting question is whether our results still hold whenever the private signal structure is such that players always commonly learn the state. Costly information acquisition is another possible extension. Finally, another interesting follow-up to this work would be to see if a similar set of results can be obtained for boundedly

rational players who do not use full Bayesian updating but are constrained by memory restrictions.

## A Appendix

### A.1 Mathematical Preliminaries

The following lemmas shall be useful in our analysis. The first lemma states that beliefs in an event—which are a martingale—form a submartingale when conditioned on the same event.

**Lemma 4.** *Let  $\mathcal{F}_1 \subseteq \mathcal{F}_2$  be sigma-algebras in a finite probability space, let  $p = \mathbb{P}[E \mid \mathcal{F}_1]$  be the prior probability of some event  $E$ , and let  $q = \mathbb{P}[E \mid \mathcal{F}_2]$  be its posterior probability. Then,*

$$\mathbb{E}[q \mid E, p] = \frac{\mathbb{E}[q^2 \mid p]}{\mathbb{E}[q \mid p]} \geq p.$$

**Proof.** Since the space is finite, we can write

$$\mathbb{E}[q \mid E, p] = \sum_{x \in [0,1]} x \cdot \mathbb{P}[q = x \mid E, p].$$

By Bayes' law,

$$= \sum_{x \in [0,1]} x \cdot \mathbb{P}[E \mid q = x, p] \cdot \frac{\mathbb{P}[q = x \mid p]}{\mathbb{P}[E \mid p]}.$$

Note that  $\mathbb{P}[E \mid p] = p$ , and that since  $\mathcal{F}_1 \subseteq \mathcal{F}_2$ ,  $\mathbb{P}[E \mid q = x, p] = x$ . Hence

$$= \sum_{x \in [0,1]} x^2 \cdot \frac{\mathbb{P}[q = x \mid p]}{p} = \frac{1}{p} \mathbb{E}[q^2 \mid p].$$

Again using the fact that  $\mathcal{F}_1 \subseteq \mathcal{F}_2$ ,  $p = \mathbb{E}[q \mid p]$ , we have shown that

$$= \frac{\mathbb{E}[q^2 \mid p]}{\mathbb{E}[q \mid p]}.$$

Finally, this is at least  $p$ , since  $\mathbb{E}[(q - p)^2 \mid p] \geq 0$ , and since  $\mathbb{E}[q \mid p] = p$ , and so  $\mathbb{E}[q^2 \mid p] \geq p^2$ . ■

The next lemma states that if a random variable taking values in the unit interval has

a mean close to one, then it must assume values close to one with high probability.

**Lemma 5.** *Let  $X$  be a random variable which takes values in  $[0, 1]$ . Suppose  $\mathbb{E}[X] \geq 1 - \varepsilon^2$  where  $\varepsilon \in (0, 1)$ . Then,*

$$\mathbb{P}[X > 1 - \varepsilon] \geq 1 - \varepsilon.$$

**Proof.** Define the random variable  $Y = 1 - X$ . Note that it suffices to show that

$$\mathbb{P}[Y \geq \varepsilon] \leq \varepsilon. \quad (9)$$

Since  $\mathbb{E}[Y] \leq \varepsilon^2$ , and since  $Y$  is non-negative, by Markov's inequality, we obtain (9). ■

## A.2 Proofs from Section 3

**Proof of Claim 1.** Suppose that a sequence  $\{\sigma_i^n\}_n$  in the set  $\mathcal{S}_i(T)$  converges to a strategy  $\sigma_i$ . Fix an action history  $a^{t-1} \in \mathcal{C}$  and private signals  $x_i^t$ . Then,  $\sigma_i^n(a^{t-1}, x_i^t) = 0$  for all  $n$  and hence  $\sigma_i(a^{t-1}, x_i^t) = 0$ . Next, fix action histories  $a^{t-1}, b^{t-1} \in A^{t-1}$  that differ only in cool-off phases and private signals  $x_i^t$ . That  $\sigma_i^n(a^{t-1}, x_i^t) = \sigma_i^n(b^{t-1}, x_i^t)$  for all  $n$  implies  $\sigma_i(a^{t-1}, x_i^t) = \sigma_i(b^{t-1}, x_i^t)$ .

Second, we show the convexity. Suppose that  $\sigma_i, \sigma_i' \in \mathcal{S}_i(T)$  and let  $\lambda \in (0, 1)$ . We show that the strategy  $\sigma_i^\lambda = \lambda\sigma_i + (1 - \lambda)\sigma_i'$  is in  $\mathcal{S}_i(T)$ . For any action history  $a^{t-1} \in \mathcal{C}$ , we have that  $\sigma_i(a^{t-1}, x_i^t) = \sigma_i'(a^{t-1}, x_i^t) = 0$  (i.e., player  $i$  chooses action  $N$ ) for any private signals  $x_i^t$ , and hence  $\sigma_i^\lambda(a^{t-1}, x_i^t) = 0$ . Next, for any action histories  $a^{t-1}, b^{t-1} \in A^{t-1}$  that differ only in cool-off phases and private signals  $x_i^t$ , we have that  $\sigma_i(a^{t-1}, x_i^t) = \sigma_i(b^{t-1}, x_i^t)$  and  $\sigma_i'(a^{t-1}, x_i^t) = \sigma_i'(b^{t-1}, x_i^t)$ . Then,  $\sigma_i^\lambda(a^{t-1}, x_i^t) = \sigma_i^\lambda(b^{t-1}, x_i^t)$ . ■

**Proof of Claim 2.** Let  $(\mathcal{C}, \mathcal{I})$  be the partition on action histories induced by the cool-off function  $T$ . First, we show that  $\mathcal{S}_i(T, \varepsilon)$  is a closed set. Let  $\{\sigma_i^n\}_n \in \mathcal{S}_i(T, \varepsilon)$  be sequence of player  $i$  strategies such that  $\sigma_i^n \rightarrow \sigma_i^*$ . Since,  $\mathcal{S}_i(T)$  is closed, it follows that  $\sigma_i^* \in \mathcal{S}_i(T)$ . Now, let  $a^{t-1} \in \mathcal{I}$  and let  $\mathbb{P}_{\sigma_i}[a_{it} = I \mid \theta = H, a^{t-1}] \geq 1 - \varepsilon$  be the probability under  $\sigma_i$ , that player  $i$  invests in the high state conditional on having reached  $a^{t-1}$ . This probability is continuous in the strategy  $\sigma_i$ . Hence,  $1 - \varepsilon \leq \lim_{n \rightarrow \infty} \mathbb{P}_{\sigma_i^n}[a_{it} = I \mid \theta = H, a^{t-1}] = \mathbb{P}_{\sigma_i^*}[a_{it} = I \mid \theta = H, a^{t-1}]$ . Hence  $\sigma_i \in \mathcal{S}_i(T, \varepsilon)$ .

Second, we show convexity. Suppose that  $\sigma_i, \sigma_i' \in \mathcal{S}_i(T, \varepsilon)$  and let  $\lambda \in (0, 1)$ . We show that the strategy  $\sigma_i^\lambda = \lambda\sigma_i + (1 - \lambda)\sigma_i'$  is in  $\mathcal{S}_i(T, \varepsilon)$ . Since,  $\mathcal{S}_i(T)$  is convex, it follows that  $\sigma_i^\lambda \in \mathcal{S}_i(T)$ . Now, fix an action history  $a^{t-1} \in \mathcal{I}$ . Consider a strategy  $\sigma_j$  where player  $j$  plays

action  $I$  with probability 0.5 after every private signal. Now, let  $q(a^{t-1})$  and  $q'(a^{t-1})$  denote the probability of reaching action history  $a^{t-1}$  under  $(\sigma_i, \sigma_j)$  and  $(\sigma'_i, \sigma_j)$  respectively. Further, define the quantity

$$\lambda(a^{t-1}) = \frac{\lambda q(a^{t-1})}{\lambda q(a^{t-1}) + (1 - \lambda)q'(a^{t-1})}.$$

This denotes the posterior probability that player  $i$  is using strategy  $\sigma_i$  conditional on  $a^{t-1}$ . Now, we have

$$\begin{aligned} \mathbb{P}_{\sigma_i^\lambda} [a_{it} = I \mid \theta = H, a^{t-1}] &= \lambda(a^{t-1})\mathbb{P}_{\sigma_i} [a_{it} = I \mid \theta = H, a^{t-1}] + (1 - \lambda(a^{t-1}))\mathbb{P}_{\sigma'_i} [a_{it} = I \mid \theta = H, a^{t-1}] \\ &\geq 1 - \varepsilon, \end{aligned}$$

which completes the proof. ■

**Proof of Lemma 2.** Denote by  $p$  player  $i$ 's belief at the action history  $a^{t-1}$ . For each possible continuation strategy  $s$  of player  $i$  (which we think of as depending only on his future signals) let  $v_H$  and  $v_L$  denote the expected payoff in the high and low state, respectively, so that the expected payoff for the continuation strategy  $s$  is given by  $pv_H + (1 - p)v_L$ . In any best response of player  $i$ , his expected payoff is given by

$$v(p) = \max_s \{pv_H + (1 - p)v_L\},$$

where the maximization is over all continuation strategies for player  $i$ . Since it is the maximum of convex functions, it is convex. To see that it is increasing, note that continuation value  $v_L \leq 0$  for every continuation strategy  $s$ , that  $v_L = v_H = 0$  for some continuation strategy  $s$ —specifically in the strategy in which the player never invests. Hence the derivative of continuation payoff  $v(p)$  is at least 0 at  $p = 0$ , and thus continuation payoff  $v(p)$ , as a function of belief  $p$ , has a non-negative subderivative in the entire interval  $[0, 1]$ . ■

**Proof of Lemma 3.** Denote by  $p$  player  $i$ 's belief at the action history  $a^{t-1}$ . Let  $s_I^*$  be the strategy in which player  $i$  invests at  $a^{t-1}$  and then never again. The conditional payoffs for this strategy are

$$v_H^* \geq (1 - \delta)(1 - c - \varepsilon), \quad v_L^* = -(1 - \delta)c.$$

where the former holds true because the opponent invests with probability at least  $1 - \varepsilon$  in the state  $\theta = H$ .

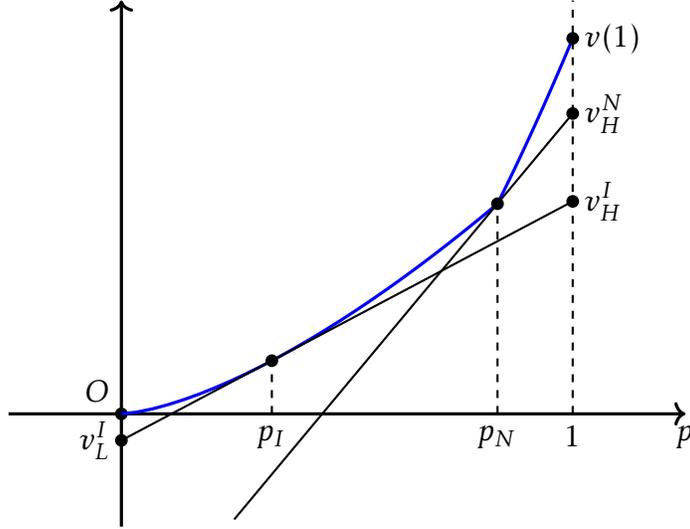


Figure 4: the continuation value  $v(p)$

Let  $s_N$  be any strategy in which player  $i$  does not invest at  $a^{t-1}$ . Then, because of the cool-off scheme, the payoffs for this strategy are

$$v_H^N \leq \delta^{T_0}. \quad (10)$$

Let  $s_I$  be any strategy in which player  $i$  invests at  $a^{t-1}$ . Then

$$v_L^I \leq -(1 - \delta)c. \quad (11)$$

Assume by contradiction that it is optimal to choose the strategy  $s_I$  at belief  $p_I$  and to choose the strategy  $s_N$  at belief  $p_N > p_I$ . Recall that the continuation payoff  $v(p)$ , defined in the proof of Lemma 2, is supported by the line  $pv_L^I + (1 - p)v_H^I$  at the belief  $p_I$  and by  $pv_L^N + (1 - p)v_H^N$  at  $p_N$ . Since it is non-decreasing and convex (Lemma 2), it follows that  $v_H^I \leq v_H^N$ . Inequality (10) implies that  $v_H^I \leq \delta^{T_0}$ . By condition (4), we have that  $v_H^I < v_H^*$ . By inequality (11) we have that  $v_L^I \leq v_L^*$ , and thus the continuation strategy  $s_I^*$  strictly dominates  $s_I$  for any belief  $p \neq 0$ . Hence, the continuation strategy  $s_I$  cannot be optimal in such a belief. Moreover, it cannot be optimal at the belief  $p = 0$  either, since it is better to not invest. We have thus reached a contradiction. ■

**Proof of Corollary 1.** It suffices to establish the corollary in the case where  $s = t + 1$ . That

is,  $a^{s-1} = a^t = (a^{t-1}, (I, I))$ . Now, we have,

$$\begin{aligned}\mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}, a_{it} = I, a_{jt} = I] &\geq \mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}, a_{jt} = I] \\ &\geq \mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}],\end{aligned}$$

where the first inequality follows from the fact that player  $i$  uses a threshold rule at  $a^{t-1}$  (Lemma 3), hence conditioning on  $a_{it} = I$  increases the expectation of player  $i$ 's private belief. The second inequality follows since player  $j$  uses a threshold rule, hence conditional on  $a_{jt} = I$ , player  $i$  learns that player  $j$ 's belief is above a threshold and hence, his beliefs move upwards. Now, by the tower property of expectations,

$$\mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}] = \mathbb{E}[\mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}, p_{it}] \mid \theta = H, a^{t-1}]$$

From Lemma 5, and since  $p_{it} = \mathbb{P}[\theta = H \mid a^{t-1}, x_i^t]$ , it follows that  $\mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}, p_{it}] \geq p_{it}$  almost surely, and so

$$\mathbb{E}[p_{it+1} \mid \theta = H, a^{t-1}] \geq \mathbb{E}[p_{it} \mid \theta = H, a^{t-1}].$$

■

**Proof of Proposition 3.** Since each strategy  $\sigma_i \in \Sigma_i$  specifies the probability  $\sigma_i(h_{it}) \in [0, 1]$  that player  $i$  invests at the private history  $h_{it} \in H_{it}$ , the strategy space  $\Sigma_i$  is the product set  $[0, 1]^{\cup_i H_{it}}$ , which is compact by Tychonoff's theorem. By Claim 2, the set  $\mathcal{S}_i(T, \varepsilon)$  is closed, thus compact, and convex. Payoffs are continuous, which follows from the fact that they are discounted exponentially and that the topology on  $\Sigma_i$  is the product topology. Hence, by Glicksberg's Theorem, the game in which the players are restricted to  $\mathcal{S}(T, \varepsilon)$  has a Nash equilibrium  $\sigma^* = (\sigma_i^*, \sigma_j^*) \in \mathcal{S}(T, \varepsilon)$ . It follows from Propositions 1 and 2 that this fixed point is, in fact, a Nash equilibrium of the unrestricted game, since any best response to any strategy in  $\mathcal{S}_j(T, \varepsilon)$  would be in  $\mathcal{S}_i(T, \varepsilon)$ . ■

**Proof of Lemma 1.** Let  $\sigma^{**}$  equal  $\sigma^*$  on-path, and off-path let both players play  $N$  under  $\sigma^{**}$ .  $\sigma^{**}$  is still a Nash equilibrium (and clearly outcome equivalent) since now, off-path, players are guaranteed utility at most zero, whereas before utilities off-path were non-negative. Also,  $\sigma^{**}$  is sequentially rational—for any belief system that is consistent with Bayes' rule on-path—since, if player  $i$  never invests then player  $j$ 's unique best response is to also never invest.

We construct the belief system  $\mu^*$  as follows. Firstly, note that beliefs on-path are uniquely determined by Bayes' rule. Now, for any observable deviation made by the

opponent, an action (one of  $\{I, N\}$ ) was taken even though it is supposed to be chosen with probability zero. We assume that in  $\mu^*$ , upon observing such an action, players update their belief as if they observed the other action, which was supposed to be chosen with probability one.

To see that  $\mu^*$  satisfies consistency, for each  $n > 1$ , define the strategy  $\sigma_i^n$  for each player  $i = 1, 2$  as follows

$$\sigma_i^n(a^{t-1}, x_i^t) = \begin{cases} 1 - \frac{1}{n} & \text{if } \sigma_i^{**}(a^{t-1}, x_i^t) = 1 \\ \frac{1}{n} & \text{if } \sigma_i^{**}(a^{t-1}, x_i^t) = 0 \\ \sigma_i^{**}(a^{t-1}, x_i^t) & \text{o.w.} \end{cases} \quad (12)$$

Note that  $\sigma_i^n$  chooses each action at each private history with positive probability. In particular,  $\sigma^n$  differs from  $\sigma^{**}$  in that whenever under  $\sigma^{**}$  player  $i$  chooses an action with probability one, under  $\sigma^n$  player  $i$  chooses that same action instead with probability  $1 - \frac{1}{n}$ . Note that this change does not depend on the agent's private history. Hence, when an observable deviation occurs under  $\sigma^{**}$ , the beliefs of the players are unchanged by assumption and are close to the beliefs generated by  $\sigma^n$  as  $n$  tends to infinity. ■

**Proof of Proposition 4.** We prove the claim in the case of the state  $\theta = H$ . The proof for the case of the state  $\theta = L$  is analogous. We proceed in two steps.

**Step 1:** Fix a strategy profile  $\sigma$ , and suppose that there exists an on-path action history  $\bar{a}^{t-1} \in A^{t-1}$  such that

$$\mathbb{E}[p_{it} \mid \theta = H, \bar{a}^{t-1}] \geq 1 - \varepsilon^2$$

for each  $i = 1, 2$ . From Lemma 5, it follows that

$$\mathbb{P}[p_{it} > 1 - \varepsilon \mid \theta = H, \bar{a}^{t-1}] \geq 1 - \varepsilon \quad (13)$$

We will show that

$$\mathbb{P}[C_t^{(1-\varepsilon)^2}(H) \mid \theta = H, \bar{a}^{t-1}] \geq (1 - \varepsilon)^2. \quad (14)$$

Note that beliefs  $p_{1t}$  and  $p_{2t}$  are independent conditional on the state  $\theta = H$  and action history  $\bar{a}^{t-1}$ , since private signals are conditionally independent. Now, consider the event

$$F_t = \left\{ \omega \in \Omega : a^{t-1}(\omega) = \bar{a}^{t-1}, p_{it}(\omega) \geq 1 - \varepsilon \text{ for each } i = 1, 2 \right\}.$$

Note that from inequality (13), we have  $\mathbb{P}[F_t \mid \theta = H, \bar{a}^{t-1}] \geq (1 - \varepsilon)^2$ . Hence, it suffices to show that  $F_t \subseteq C_t^{(1-\varepsilon)^2}(H)$ . By the result of [Monderer and Samet \(1989\)](#), it suffices to show that the event  $F_t$  is  $(1 - \varepsilon)^2$ -evident (i.e.,  $F_t \subseteq B_t^{(1-\varepsilon)^2}(F_t)$ ) and that  $F_t \subseteq B_t^{(1-\varepsilon)^2}(H)$ . The latter follows since  $F_t \subseteq B_t^{1-\varepsilon}(H) \subseteq B_t^{(1-\varepsilon)^2}(H)$ . Thus, we show the former. At any  $\omega \in F_t$ , in period  $t$  player  $i$ 's belief about the event  $F_t$  is

$$\mathbb{P}[F_t \mid \bar{a}^{t-1}, x_i^t] \geq p_{it}(\omega) \mathbb{P}[F_t \mid \theta = H, \bar{a}^{t-1}, x_i^t] \geq (1 - \varepsilon)^2.$$

This implies that  $\omega \in B_t^{(1-\varepsilon)^2}(F_t)$ . That is,  $F_t \subseteq B_t^{(1-\varepsilon)^2}(F_t)$ . Hence, inequality (14) follows. Moreover, since  $C_t^{(1-\varepsilon)^2}(H) \subseteq C_t^{(1-\varepsilon)^2(1-\varepsilon^2)}(H)$ , we have that

$$\mathbb{P}[C_t^{(1-\varepsilon)^2(1-\varepsilon^2)}(H) \mid \theta = H, \bar{a}^{t-1}] \geq (1 - \varepsilon)^2.$$

**Step 2:** Fix any  $\varepsilon \in (0, 1)$ , and let  $\bar{T} \in \mathbb{N}$  be such that for each  $i = 1, 2$  and  $t \geq \bar{T}$ ,

$$\mathbb{E}[p_{it} \mid \theta = H] \geq 1 - \left(\frac{\varepsilon^2}{2}\right)^2.$$

Note that there exists such a  $\bar{T}$ , since each player individually learns the state. By the tower property of conditional expectations,

$$\mathbb{E}[p_{it} \mid \theta = H] = \mathbb{E}[\mathbb{E}[p_{it} \mid \theta = H, a^{t-1}] \mid \theta = H]$$

From Lemma 5, we have that for each  $i = 1, 2$ ,

$$\mathbb{P}\left[\mathbb{E}[p_{it} \mid \theta = H, a^{t-1}] \geq 1 - \frac{\varepsilon^2}{2} \mid \theta = H\right] \geq 1 - \frac{\varepsilon^2}{2}.$$

Then,

$$\mathbb{P}\left[\mathbb{E}[p_{it} \mid \theta = H, a^{t-1}] \geq 1 - \varepsilon^2 \text{ for each } i = 1, 2 \mid \theta = H\right] \geq 1 - \varepsilon^2.$$

Hence, for each  $t \geq \bar{T}$ ,

$$\mathbb{P}[C_t^{(1-\varepsilon)^2(1-\varepsilon^2)}(H) \mid \theta = H] \geq (1 - \varepsilon)^2(1 - \varepsilon^2),$$

which establishes the desired result. ■

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