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Working Paper

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Working Paper, No. 2005-14

Provided in Cooperation with:

Department of Economics, Rutgers University

Suggested Citation: Neyman, Abraham; Okada, Daijiro (2005) : Growth of strategy sets, entropy and nonstationary bounded recall, Working Paper, No. 2005-14, Rutgers University, Department of Economics, New Brunswick, NJ

This Version is available at:

<https://hdl.handle.net/10419/31298>

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GROWTH OF STRATEGY SETS, ENTROPY, AND NONSTATIONARY BOUNDED RECALL

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Neyman's research is partly supported by Israel Science Foundation grants 382/98 and 263/03. Okada gratefully acknowledges support from The Research Council at Rutgers University.

ABSTRACT. One way to express bounded rationality of a player in a game theoretic models is by specifying a set of feasible strategies for that player. In dynamic game models with finite automata and bounded recall strategies, for example, feasibility of strategies is determined via certain complexity measures: the number of states of automata and the length of recall. Typically in these models, a fixed finite bound on the complexity is imposed resulting in finite sets of feasible strategies. As a consequence, the number of distinct feasible strategies in any subgame is finite. Also, the number of distinct strategies induced in the first T stages is bounded by a constant that is independent of T .

In this paper, we initiate an investigation into a notion of feasibility that reflects varying degree of bounded rationality over time. Such concept must entail properties of a strategy, or a set of strategies, that depend on time. Specifically, we associate to each subset Ψ_i of the full (theoretically possible) strategy set a function ψ_i from the set of positive integers to itself. The value $\psi_i(t)$ represents the number of strategies in Ψ_i that are distinguishable in the first t stages. The set Ψ_i may contain infinitely many strategies, but it can differ from the fully rational case in the way ψ_i grows reflecting a broad implication of bounded rationality that may be alleviated, or intensified, over time.

We examine how the growth rate of ψ_i affects equilibrium outcomes of repeated games. In particular, we derive an upper bound on the individually rational payoff of repeated games where player 1, with a feasible strategy set Ψ_1 , plays against a fully rational player 2. We will show that the derived bound is tight in that a specific, and simple, set Ψ_1 exists that achieves the upper bound.

As a special case, we study repeated games with non-stationary bounded recall strategies where the length of recall is allowed to vary in the course of the game. We will show that a player with bounded recall can guarantee the minimax payoff of the stage game even against a player with full recall so long as he can remember, at stage t , at least $K \log t$ stages back for some constant $K > 0$. Thus, in order to guarantee the minimax payoff, it suffices to remember only a vanishing fraction of the past. A version of the folk theorem is provided for this class of games.

(*Journal of Economic Literature* Classification Number: C72, C73)

KEYWORDS: Bounded Rationality, Strategy Set Growth, Strategic Complexity, Nonstationary Bounded Recall, Repeated Games, Entropy

1. INTRODUCTION

Many social (economic, political, etc.) interactions have been modeled as formal games. The idea that players in a game are rational is reflected in several aspects of the model, as well as in the analysis performed (optimization, equilibrium). When a game theorist employs a particular solution concept, there is an implicit understanding that players optimize or find a best response to others' actions from their feasible set of strategies. Aside from the assumption that the players can perform computations necessary for such tasks, it is assumed that players can carry out any strategy in the specified strategy set should they choose to play it. While this latter assumption may seem innocuous in a model where few strategies are available to each player,¹ e.g., prisoner's dilemma and the battle of the sexes, it may be criticized as being unrealistically rational in more complex models where the theoretical definition of strategy leads to a strategy set that contains a large number of choices, many of which are impractically complex.

A case in point is models of dynamic interaction including repeated games in their most basic formulation. In repeated games, a strategy is a set of history-contingent plans of action. Even when the underlying stage game contains only a few possible actions, the number and complexity of histories quickly grows as time passes. Consequently, the set of strategies contains a large number of elements, and many of them require the capability to process arbitrarily complex history for their implementation.

The idea that the assumption of fully, or unboundedly, rational players is unrealistic is not new (Simon (1955), Simon (1972), Aumann (1981), Aumann (1997)). There have been many attempts to model feasible (implementable) sets of strategies that reflect some aspects of the bounded rationality of players. Finite automata, bounded recall, and Turing machines are a few of the approaches taken. These models are useful because they provide us with quantitative measures of complexity of strategies, e.g., the number of states of automata and the length of recall.²

¹See however Anderlini (1990).

²Variants of complexity measure associated with a Turing machine include the number of bits needed to implement a strategy by Turing machines with a bounded amount of tape (Stearns (1997)), and algorithmic or Kolmogorov complexity (Lacôte (2005), Neyman (2003)).

Existing literature on bounded complexity in repeated games considers models where the complexity of strategies is fixed in the course of a long interaction. In the case of finite automata and bounded recall (e.g., Ben-Porath (1993), Lehrer (1988)), a single integer - the number of states or the length of recall - fully describes the set of feasible strategies. As a consequence, the set of feasible strategies, e.g., those implemented by finite automata of a fixed size, is finite. Moreover, the number of distinct feasible strategies in any subgame as well as the number of distinct strategies in the first T stages of the interaction is bounded. While this literature has supplied significant insights and formal answers to questions such as “when is having a higher complexity advantageous?” (op. cit.) or “when does bounded complexity facilitate cooperation?” (e.g., Neyman (1985), Neyman (1997)), we argue below that it would be fruitful to extend the analysis to include a salient feature and an implication of bounded rationality in dynamic decision-making that are not captured by the existing approaches.

An important feature of an economic decision-maker (consumer, firm, government, trade and labor union, etc.) is described by its set of feasible decision rules. These rules, strategies or policies, are neither unimaginably complex or mindlessly simple. Nor is the set of feasible decision rules fixed over time. Technological progresses inevitably influence the sophistication and efficiency of handling information necessary to determine the behavior of these agents. Firms make investments in order to update technology and change organizational structure in an effort to improve their abilities to process information and arrive at better decisions, e.g., efficient allocation of resources within firms or streamlining of decision-making in an uncertain, often strategic, environment. Such changes bring about the transformation of the set of possible decision rules over time.

A decision rule, in its abstract formulation, is a rule, or a function, that transforms information into actions. Information has to be, first of all, translated into a form (language) that can be communicated (in the case of an organization or a team) and then interpreted by the decision-maker. In economic applications, information relevant to decision-making is often some data, signal, message, history, etc., that modifies the decision-maker’s perception about the environment, including other decision-makers’ actions and information they themselves possess. As the

ability to process such information improves (thereby making the agent capable of recognizing her environment in finer detail), the decision-maker would become able to implement more flexible and versatile decision rules.

Internet commerce offers one of many cases that are pertinent to this argument. Internet vendors collect detailed information on the buying habits of consumers. An investment in technologies to collect and store such information, or expenditures on purchasing such information from a third party, enables the sellers to devise more flexible - customer-specific - marketing strategies that would otherwise not be feasible. Since competing companies are likely to utilize similar information, this type of investment enables the company to gauge its rivals' strategic capabilities. Thus we need a model of an agent, or a player, whose strategic capabilities change over time.

As argued in the beginning, complexity of repeated games as a model of interactive decision-making stems, in part, from the wealth of strategies from which the theory allows players to choose. The number of theoretically possible strategies is double-exponential in the number of repetitions. This is due to the fact that the number of histories grows exponentially with the number of repetitions and also because we count strategies that map histories into actions in all possible ways. Some, in fact most,³ strategies are too complicated to admit a short and practically implementable description: a short description of a strategy requires an efficient encoding of histories, but some histories may have no shorter descriptions than simply writing them out in their entirety. These considerations motivate research on bounded rationality in long-term interaction in general, and on various measures of complexity of implementing strategies and their effects on equilibrium outcomes in particular.

Our aim in this paper is to take a first step into formalizing the idea of temporal change in the degree of bounded rationality and examining its consequences in long-term interactions. Thus, at the conceptual level, our motivation may be paraphrased as follows. Players with bounded rationality are limited by the set of feasible strategies, but computational resources available to the players may expand

³For instance, if a feasible set of strategies contains K distinct strategies, then one needs close to $\log K$ bits (for sufficiently large K) to encode most of them.

or contract over time. As a consequence, the limitation would vary over time and, in particular, there may not be a finite upper bound on complexity of strategies for the entire horizon of the game. Such considerations of the more general aspects of bounded rationality cannot be captured by a model with a finite set of feasible strategies. Thus we are led to considering in general a feasible set consisting of infinitely many strategies. The question that arises then is : “What are the characteristics of an infinite strategy set that (1) may be derived from an explicit description (e.g., by means of a complexity measure) of a feasible strategy set and (2) can be used to provide bounds on equilibrium outcomes?”

A common feature of feasible strategy sets described by means of any complexity measure is that it contains fewer elements than the fully rational case. As we take aim at a temporal aspect of an infinite strategy set, we shall consider how the number of strategies induced in the first t stages of the game grows. Specifically, we associate to each subset Ψ_i of the full (theoretically possible) strategy set a function ψ_i from the set of positive integers to itself. The value $\psi_i(t)$ represents the number of strategies in Ψ_i that are distinguishable in the first t stages. The feasible strategy set Ψ_i may contain infinitely many strategies, but it can differ from the fully rational case in the way ψ_i grows reflecting a broad implication of bounded rationality that may vary over time.⁴ To be more precise, for each t , let $\Psi_i(t)$ be the projection of Ψ_i to the first t stages of the game. Then $\psi_i(t)$ is the number of equivalence classes of strategies in $\Psi_i(t)$. If Ψ_i contains all theoretically possible strategies, then, as mentioned in the beginning, $\psi_i(t)$ is double-exponential in t . Thus it is of interest to study how outcomes of repeated games are affected by various conditions on the rate of growth of $\psi_i(t)$.

Since no structure is imposed on the strategies that belong to Ψ_i , it appears to be difficult, if not impossible, to derive results purely on the basis of how $\psi_i(t)$ grows. For this reason, and as a first undertaking in this line of research, we will study a simple case of two-person repeated games in which player 1 with a feasible

⁴In this paper, the feasible set Ψ_i , and hence the growth of the function ψ_i , is exogenously given. We recognize the importance of studying models where players may invest in order to expand their strategic possibilities, thereby endogenizing the growth rate of ψ_i . This certainly deserves further research. The work reported here provides limits to what can and cannot be achieved by such a choice.

set Ψ_1 plays against fully rational player 2. The payoff in the repeated games is the long-run average of the stage payoffs. In this setup we will show that there is a continuous function $U : \mathbb{R}_+ \rightarrow \mathbb{R}$ such that player 1 cannot guarantee more than $(\text{cav } U)(\gamma)$, the concavification of U , whenever $\psi_1(t)$ grows at most as fast as $2^{\gamma t}$. Moreover, this bound is tight. It will be seen that the function U is defined using the concept of entropy and has the property that $U(0)$ is the maximin value of the stage game in pure actions and $U(\gamma)$ is the usual minimax value for sufficiently large γ .

As a concrete case of an infinite feasible strategy set arising from a complexity consideration, we will study the repeated game with nonstationary bounded recall strategies, which is a model of a player whose memory of the past varies over time and hence, it is an extension of classical stationary bounded recall strategies. As a direct consequence of a theorem mentioned above, we will show that a player with nonstationary bounded recall can only guarantee the maximin payoff in pure actions of the stage game if the size of his recall is less than $K_0 \log t$ at stage t for some constant $K_0 > 0$. In addition, we will show that there is a constant $K_1 > K_0$ such that if, for all sufficiently large t , the recall at stage t is at least $K_1 \log t$, the minimax payoff of the stage game can be guaranteed. Hence, in order to secure the minimax payoff of the stage game even against a player with full recall, one needs to remember a long enough yet still only a vanishing fraction of the past history.

In order to avoid possible confusion, we point out that, as is standard in the literature, we consider mixed strategies so long as their support lies in the set of feasible pure strategies. A possible interpretation of mixed strategies in games in general is that they are distributions of pure strategies in a population of potential players. In the context of games we analyze in this paper, a fully rational player faces one of the players randomly drawn from this population. Thus a mixed strategy of her opponent reflects the uncertainty that she faces as to which feasible pure strategy is employed by this particular opponent.

We will set the notation used throughout the paper and formalize the idea of the growth of strategy sets in Section 2. Some examples, including nonstationary bounded recall strategies, will also be discussed in this section. Section 3 contains some results on the values of two-person repeated games where a player with

bounded rationality plays against a fully rational player. As mentioned above these results are based purely on the rate of growth of strategy sets regardless of which strategies they contain. In Section 4, nonstationary bounded recall strategies are examined.

2. GROWTH OF STRATEGY SETS

Let $G = (A_i, g_i)_{i \in I}$ be a finite game in strategic form. The set of player i 's mixed actions is denoted by $\Delta(A_i)$. Henceforth we refer to G as a stage game.

In the repeated version⁵ of G , written G^* , a pure strategy of a player is a rule that assigns an action to each history. A history by definition is a finite string of action profiles (including the null string which is denoted by ϵ). Thus the set of all histories is $A^* = \bigcup_{t=0}^{\infty} A^t$ where $A = \prod_{i \in I} A_i$ and $A^0 = \{\epsilon\}$. A pure strategy of player i is a mapping $\sigma_i : A^* \rightarrow A_i$. Let Σ_i be the set of all pure strategies of player i . The set of mixed strategies of player i is denoted by $\Delta(\Sigma_i)$.

We say that two pure strategies of player i , σ_i and σ'_i , are equivalent up to the t -th stage if, for every profile of other players' strategies σ_{-i} , the sequence of action profiles induced by (σ_i, σ_{-i}) and (σ'_i, σ_{-i}) are identical up to, and including, stage t . If two strategies are equivalent up to the t -th stage for every t , then we simply say they are equivalent. Equivalence between two mixed strategies is defined similarly by comparing the induced distributions over sequence of action profiles.

Let us denote by m_i the number of actions available to player i , i.e., $m_i = |A_i|$, and let $m = \prod_{i \in I} m_i = |A|$. We note first that the number of strategies available to player i in the first t stages of a repeated game is⁶ $m_i^{m^0} \times \dots \times m_i^{m^{t-1}} = m_i^{\frac{m^t - 1}{m - 1}}$. This number is double exponential in t .

Suppose that player i has access to a set of strategies, $\Psi_i \subset \Sigma_i$. This would be the case, for example, when there is limitations on some aspects of complexity of his strategies. For each positive integer t , let $\Psi_i(t)$ be formed by identifying

⁵In this paper we consider the most basic model of repeated games, i.e., ones with complete information and perfect monitoring.

⁶The number of reduced strategies available to player i in the first t stages is $m_i^{\frac{m^t - 1}{m - 1}}$ where $m_{-i} = \prod_{j \neq i} m_j$.

strategies in Ψ_i that are equivalent up to the t -th stage.⁷ Let $\psi_i(t)$ be the number of elements in $\Psi_i(t)$. Any consideration on strategic complexity gives rise to some strategy set Ψ_i and thus limitation on the rate of growth of $\psi_i(t)$. For example, if player i 's feasible strategies are described by finite automata with a fixed number of states, then Ψ_i is a finite set and $\Psi_i(t) = \Psi_i$ for all sufficiently large⁸ t . In this case $\psi_i(t) = O(1)$. Below we illustrate some examples of feasible strategy sets with various rate of growth of $\psi_i(t)$.

Example 1. In this example we provide a framework for nonstationary bounded recall strategies that we will examine in detail in Section 4. Recall that a stationary bounded recall strategy of size k is a strategy that depends only on at most the last k -terms of the history. More precisely, for each pure strategy $\sigma_i \in \Sigma_i$, define a strategy $\sigma_i \bar{\wedge} k : A^* \rightarrow A_i$ by

$$(\sigma_i \bar{\wedge} k)(a_1, \dots, a_t) = \begin{cases} \sigma_i(a_1, \dots, a_t) & \text{if } t \leq k, \\ \sigma_i(a_{t-k+1}, \dots, a_t) & \text{if } t > k. \end{cases}$$

The set of stationary bounded recall strategies of size k is denoted by $\bar{\mathbf{B}}_i(k)$, i.e.

$$\bar{\mathbf{B}}_i(k) = \{\sigma_i \bar{\wedge} k : \sigma_i \in \Sigma_i\}.$$

It is clear that the number of distinct strategies, i.e. the number of equivalence classes, in $\bar{\mathbf{B}}_i(k)$ is at most the number of distinct functions from $\bigcup_{\ell=0}^k A^\ell$ to A_i which is of the order $m_i^{O(m^k)}$.

Now consider a function $\kappa : \mathbb{N} \rightarrow \mathbb{N} \cup \{0\}$ with $\kappa(t) \leq t - 1$. For each $t \in \mathbb{N}$, the value $\kappa(t)$ represents the length of recall at stage t . A κ -recall strategy of player i is a pure strategy that plays like a stationary bounded recall strategy of size k whenever $\kappa(t) = k$ regardless of the time index t . Formally, for each $\sigma_i \in \Sigma_i$ define a strategy $\sigma_i \wedge \kappa : A^* \rightarrow A_i$ by

$$(\sigma_i \wedge \kappa)(a_1, \dots, a_t) = \sigma_i(a_{t-\kappa(t)+1}, \dots, a_t).$$

⁷If two strategies in Ψ_i are equivalent, then they are never distinguished in $\Psi_i(t)$ for any t . So the reader may consider Ψ_i to be the set of equivalence classes of strategies.

⁸In fact, this holds for all $t \geq k^2$ and $2^{ck \log k} \leq |\Psi_i| \leq 2^{dk \log k}$ where k is the bound on the number of states of automata and c and d are positive constants.

Observe that in this definition player i must take the same action at stage t and t' where $\kappa(t) = \kappa(t') = k$ so long as he observes the same sequence of action profiles in the last k stages. Thus, the set of κ -recall strategies is

$$\mathbf{B}_i(\kappa) = \{\sigma_i \wedge \kappa : \sigma_i \in \Sigma_i\}.$$

Set $\Psi_i = \mathbf{B}_i(\kappa)$. Then from its definition it is clear that there is a canonical embedding of Ψ_i into $\prod_{k \in \kappa(\mathbb{N})} \bar{\mathbf{B}}(k)$ as well as a canonical embedding of $\Psi_i(t)$ into $\prod_{k \in \kappa(\{1, \dots, t\})} \bar{\mathbf{B}}(k)$ for each t . Hence

$$\psi_i(t) \leq \prod_{k \in \kappa(\{1, \dots, t\})} m_i^{m^k} \leq m_i^{c m^{\bar{\kappa}(t)}}$$

for some constant c (in fact, $c = m/(m-1)$) where $\bar{\kappa}(t) = \max_{s \leq t} \kappa(s)$.

Example 2. A strategy of player i is said to be oblivious (O'Connell and Stearns (1999)) if it depends only on the history of his own actions. That is, $\sigma_i : A^* \rightarrow A_i$ is oblivious if $\sigma_i((a_{i1}, a_{-i1}), \dots, (a_{it}, a_{-it}))$ is independent of a_{-i1}, \dots, a_{-it} . The set of oblivious strategies of player i is denoted by \mathbf{O}_i . Every oblivious strategy induces a sequences of player i 's actions. Also, any sequence of player i 's actions can be induced by an oblivious strategy. So the set of equivalence classes of strategies in \mathbf{O}_i can be identified with the set of sequences of player i 's actions, A_i^∞ . Hence if $\Psi_i = \mathbf{O}_i$, then $\Psi_i(t)$ is identified with A_i^t and so $\psi_i(t) = m_i^t$. For each sequence $\mathbf{a} = (a_{i1}, a_{i2}, \dots) \in A_i^\infty$, we denote by $\sigma_i \langle \mathbf{a} \rangle$ the oblivious strategy that takes action a_t at stage t regardless of the past history.

In all the examples that follow, consider a two person game in which each player has two actions, $A_1 = A_2 = \{0, 1\}$.

Example 3. For each integer $k \geq 0$, define a strategy $\sigma_1^{(k)}$ as follows. For each history h , let $N(1|h)$ be the number of times player 2 chose action 1 in h .

$$\sigma_1^{(k)}(h) = \begin{cases} 1 & \text{if } N(1|h) \geq k \\ 0 & \text{otherwise.} \end{cases}$$

Let $\Psi_1 = \{\sigma_1^{(0)}, \sigma_1^{(1)}, \dots\}$. Then $\Psi_1(t) = \{\sigma_1^{(0)}, \dots, \sigma_1^{(t-1)}\}$ and $\psi_i(t) = t$.

Example 4. A prefix of a history $h = (h_1, \dots, h_t)$ is any of its initial segment $h' = (h_1, \dots, h_s)$, $s \leq t$. A set of histories $L \subset \bigcup_{t=1}^{\infty} H_t$ is said to be prefix-free

if no element of L is a prefix of another. For each positive integer t , let $L(t) = L \cap (H_1 \cup \dots \cup H_{t-1})$; $L(t)$ is prefix-free and $L(t) \subset L(t+1)$. Define a strategy σ_1^L as follows.

$$\sigma_1^L(h_1, \dots, h_t) = \begin{cases} 1 & \text{if } (h_1, \dots, h_s) \in L \text{ for some } s \leq t, \\ 0 & \text{otherwise.} \end{cases}$$

This is a generalization of the trigger strategy: σ_1^L takes action 1 forever as soon as a history in L occurs. Let \mathcal{L} be the class of all prefix-free sets of histories. Take a subset \mathcal{M} of \mathcal{L} and define Ψ_1 to be the set of player 1's strategies σ_1^M with $M \in \mathcal{M}$. Let us examine $\Psi_1(t)$ and $\psi_1(t)$.

It is easy to verify that, for any L and M in \mathcal{L} , σ_1^L and σ_1^M are equivalent up to the t -th stage whenever $L(t) = M(t)$. Then we have⁹ $\psi_1(t) \leq |\mathcal{M}(t)|$ where $\mathcal{M}(t) = \{M(t) : M \in \mathcal{M}\}$. Examples of \mathcal{M} can be constructed so that the corresponding function $\psi_1(t)$ is, e.g., $O(t^p)$ for a given $p \geq 1$, or $O(2^{\alpha t})$ for $0 < \alpha < 1$.

3. GAMES AGAINST A FULLY RATIONAL PLAYER

We now derive a few consequences of bounded rationality implied by a growth rate of $\psi_i(t) = |\Psi_i(t)|$. We emphasize that the nature of the feasible strategy set Ψ_i is completely arbitrary. It may include infinitely many strategies and also the strategies that cannot be represented by any finite state machines or finitely bounded recall.

Various forms of the folk theorem assert that any feasible payoff vector that gives each player at least his individually rational (I.R.) payoff can be an equilibrium outcome of the repeated game. Thus two repeated games with the same set of feasible payoffs may differ in the set of equilibrium payoff as a result of the difference in the I.R. payoffs. In the repeated game with perfect monitoring played by fully rational players, e.g., Aumann and Shapley (1994), the I.R. payoff of the repeated game coincides with that of the stage game. This is because, for every strategy profile of the other players, a player has a strategy that yields him at least his I.R. payoff of the stage game in the long run. In particular, the minimax theorem implies that, in a two-person game, each player has a repeated game strategy that yields at least the stage game I.R. payoff in the long run regardless of the other

⁹Some histories are not compatible with the strategy, hence the inequality.

player's strategy. However, when the set of feasible strategies of a player differs from the fully rational case, the I.R. payoff of the repeated game may be different from that of the stage game, and, accordingly, the set of equilibrium payoffs may differ from that of the standard folk theorem.

In models of repeated games where the sets of feasible strategies are specified via bounds on some complexity measure, and therefore they differ from the fully rational case, it is essential to know the relationship between the complexity bounds and individually rational payoffs before proceeding to the question of equilibria. In fact, once individually rational payoffs are characterized, and strategies that achieve such payoffs are found, versions of the folk theorem follow in a relatively straight forward manner (Lehrer (1988), Ben-Porath (1993)). The reader will see that this is the case in the next section on nonstationary bounded recall.

Thus, our focus in this, and the next, section will be what payoff a player with bounded rationality, implied by a specified rate of growth of ψ_i , can guarantee or defend in a repeated game. As we mentioned in the introduction, we study a benchmark case for which we can obtain concrete results in this abstract setting: two-person repeated games where a player with bounded rationality plays against a fully rational player. We point out that our results apply to any measure of strategic complexity that gives rise to a feasible strategy set satisfying our condition on the rate of growth $\psi_1(t)$.

We shall follow the following notational rule. Actions of player 1 and 2 in the stage game are denoted by a and b , respectively, and their strategies in the repeated game are denoted by σ and τ , respectively, with sub- or superscripts and other affixes added as necessary. The payoff function of player 1, g_1 , will be denoted simply by g . Let w be player 1's maximin payoff in the stage game where max and min are taken over the pure actions: $w = \max_{a \in A_1} \min_{b \in A_2} g(a, b)$. This is the worst payoff that player 1 can guarantee himself for sure in the stage game. Also, let v be the minimax payoff to player 1: $v = \min_{b \in \Delta(A_2)} \max_{a \in A_1} g(a, b) = \max_{a \in \Delta(A_1)} \min_{b \in A_2} g(a, b)$. For a pair of repeated game strategies $(\sigma, \tau) \in \Sigma_1 \times \Sigma_2$, we write $g_T(\sigma, \tau)$ for player 1's average payoff in the T -th stage.

3.1. Slowly Growing Strategy Set. Recall that $\Psi_1(t)$ is formed by identifying strategies in Ψ_1 that are equivalent up to the t -th stage and $\psi_1(t) = |\Psi_1(t)|$.

Our first theorem states that if the growth rate of $\psi_1(t)$ is subexponential in t , then player 1 cannot guarantee more than the maximin payoff in pure actions, w , in the long run. We first present a lemma which provides a bound on player 1's minimax payoff in the repeated game for an arbitrary feasible set Ψ_1 . Set $\|g\| = 2 \max\{|g(a, b)| : a \in A_1, b \in A_2\}$.

Lemma 1. *For every $\Psi_1 \subset \Sigma_1$ and every nondecreasing¹⁰ sequence of positive integers $\{t_k\}_{k=1}^\infty$, there exists $\tau^* \in \Sigma_2$ such that*

$$g_{t_k}(\sigma, \tau^*) \leq w + \|g\| \frac{1}{t_k} \sum_{\ell=1}^k \log_2 \psi_1(t_\ell)$$

for all $\sigma \in \Psi_1$ and $k = 1, 2, \dots$

Proof: We construct the strategy $\tau^* \in \Sigma_2$ as follows. Fix a stage t and let ℓ be the unique index with $t_{\ell-1} < t \leq t_\ell$. If a history $h = (h_1, \dots, h_{t-1}) = ((a_1, b_1), \dots, (a_{t-1}, b_{t-1}))$ is observed, let $\Psi_1(t_\ell, h)$ be the set of player 1's strategies in $\Psi_1(t_\ell)$ that are compatible with h , i.e., $\sigma \in \Psi_1(t_\ell, h)$ if, and only if, $\sigma \in \Psi(t_\ell)$, $\sigma(\epsilon) = a_1$, and $\sigma(h_1, \dots, h_{s-1}) = a_s$ for all $s = 2, \dots, t-1$. For each $a \in A_1$, let $\Psi_1(t_\ell, h, a)$ be the set of strategies in $\Psi_1(t_\ell, h)$ that takes the action a after the history h , i.e., $\Psi_1(t_\ell, h, a) = \{\sigma \in \Psi_1(t_\ell, h) : \sigma(h) = a\}$. Choose $a(h) \in A_1$ such that $|\Psi_1(t_\ell, h, a(h))| \geq |\Psi_1(t_\ell, h, a)|$ for all $a \in A_1$. The action $a(h)$ may be considered the most likely action taken by player 1 after the history h . Now define τ^* by

$$\tau^*(h) \in \operatorname{argmin}_{b \in A_2} g(a(h), b).$$

Clearly, $\{\Psi_1(t_\ell, h, a) \mid a \in A_1\}$ forms a partition of $\Psi_1(t_\ell)$. From the definition of $a(h)$ it follows that $|\Psi_1(t_\ell, h, a)| \leq \frac{1}{2} |\Psi_1(t_\ell, h)|$ for all $a \neq a(h)$. Thus, if $h' = hh_t = (h_1, \dots, h_{t-1}, h_t)$ and $h_t = (a_t, b_t)$ with $a_t \neq a(h)$, then

$$(1) \quad |\Psi_1(t_\ell, h')| \leq \frac{1}{2} |\Psi_1(t_\ell, h)|.$$

Fix $\sigma \in \Psi_1$ and let $(h_1, h_2, \dots) = ((a_1, b_1), (a_2, b_2), \dots)$ be the play generated by (σ, τ^*) . For each t , let $I_t = 0$ or 1 according to $a_t = a(h_1, \dots, h_{t-1})$ or $a_t \neq$

¹⁰In this paper, we use the terms “nondecreasing” and “increasing” (resp. “nonincreasing” and “decreasing”), rather than “increasing” and “strictly increasing” (resp. “decreasing” and “strictly decreasing”).

$a(h_1, \dots, h_{t-1})$. Then (1) implies that

$$\sum_{t=t_{\ell-1}+1}^{t_\ell} \mathbf{I}_t \leq \log_2 |\Psi_1(t_\ell, (h_1, \dots, h_{t_{\ell-1}}))| \leq \log_2 \psi_1(t_\ell) \quad \text{for all } \ell = 1, 2, \dots$$

That is, the number of stages t with $t_{\ell-1} + 1 \leq t \leq t_\ell$ at which player 1's action differs from $a(h_1, \dots, h_{t-1})$ is at most $\log_2 \psi_1(t_\ell)$. Hence

$$\sum_{t=t_{\ell-1}+1}^{t_\ell} g(h_t) \leq \sum_{t=t_{\ell-1}+1}^{t_\ell} \left((1 - \mathbf{I}_t)w + \mathbf{I}_t \frac{\|g\|}{2} \right) \leq (t_\ell - t_{\ell-1})w + \|g\| \log_2 \psi_1(t_\ell).$$

Summing over $\ell = 1, \dots, k$ (where $t_0 = 0$) we have

$$\sum_{t=1}^{t_k} g(h_t) \leq t_k w + \|g\| \sum_{\ell=1}^k \log_2 \psi_1(t_\ell).$$

Q.E.D.

If Ψ_1 is a finite set, e.g., the set of finite automata of a bounded size, then there is a \hat{t} such that $\Psi_1(t) = \Psi_1$ for all $t \geq \hat{t}$. Thus we conclude¹¹

Corollary 1. *For every finite subset Ψ_1 of Σ_1 there exists $\tau^* \in \Sigma_2$ such that*

$$g_T(\sigma, \tau^*) \leq w + \|g\| \frac{\log_2 |\Psi_1|}{T}$$

for all $\sigma \in \Psi_1$ and $T = 1, 2, \dots$

Theorem 1. *Suppose that $\frac{\log_2 \psi_1(t)}{t} \xrightarrow{t \rightarrow \infty} 0$. Then there is a strategy $\tau^* \in \Sigma_2$ such that*

$$\overline{\lim}_{T \rightarrow \infty} \max_{\sigma \in \Psi_1} g_T(\sigma, \tau^*) \leq w.$$

Proof: Let $\{t_k\}_{k=1}^\infty$ be an increasing sequence of positive integers satisfying the following properties: (A) $\frac{t_{k+1} - t_k}{t_k} \xrightarrow{k \rightarrow \infty} 0$, and (B) $\frac{\log_2 \psi_1(t_{k+1})}{t_{k+1} - t_k} \xrightarrow{k \rightarrow \infty} 0$. It is easy to verify that such a sequence exists under the condition of the theorem.

Lemma 1 and (B) imply that there is a $\tau^* \in \Sigma_2$ such that, for every $\varepsilon > 0$, $g_{t_k}(\sigma, \tau^*) \leq w + \varepsilon/2$ for all $\sigma \in \Psi_1$ and all sufficiently large k . Hence, (A) implies that $g_T(\sigma, \tau^*) < w + \varepsilon$ for all $\sigma \in \Psi_1$ and all sufficiently large T . **Q.E.D.**

¹¹This result first appeared in Neyman and Okada (2000b) in a study of repeated games with finite automata.

Note that whether player 1 can actually attain w or not depends on what strategies are in Ψ_1 . For example, if $a^* = \operatorname{argmax}_{a \in A_1} \min_{b \in A_2} g(a, b)$, and a strategy that takes a^* in every stage is available, then w can be achieved by using such a strategy.

3.2. Growth of Strategy Sets and Entropy. In this section we prove a generalization of Theorem 1 for the case when $\frac{\log_2 \psi_1(t)}{t}$ converges to an arbitrary positive number. To do this we will use the concept of entropy and its properties which we will now recall.¹²

Let X be a random variable that takes values in a finite set Ω and let $p(x)$ denote the probability that $X = x$ for each $x \in \Omega$. Then the entropy of X is defined as

$$H(X) = - \sum_{x \in \Omega} p(x) \log_2 p(x)$$

where $0 \log_2 0 \equiv 0$. The entropy as a function of the distribution p is uniformly continuous (in L_1 -norm), concave, and $0 \leq H(X) \leq \log_2 |\Omega|$ where the lower bound 0 is achieved by any one of the degenerate distributions, $p(x) = 1$ for some $x \in \Omega$, and the upper bound is achieved by the uniform distribution, $p(x) = \frac{1}{|\Omega|}$ for all $x \in \Omega$.

The conditional entropy of a random variable X given another random variable Y is defined as follows. Given the event $Y = y$, let $H(X|y)$ be the entropy of X with respect to the conditional distribution of X given y , that is,

$$H(X|y) = - \sum_x p(x|y) \log_2 p(x|y).$$

Then the conditional entropy of X given Y is the expected value of $H(X|y)$ with respect to the (marginal) distribution of Y :

$$H(X|Y) = E_Y[H(X|y)] = \sum_y p(y) H(X|y).$$

Conditioning reduces entropy, i.e., $H(X) \geq H(X|Y) \geq H(X|Y, Z)$, and $H(X|Y) = H(X)$ if, and only if, X and Y are independent. An important consequence of the definition of the conditional entropy is the ‘‘chain rule’’:

$$H(X_1, \dots, X_T) = H(X_1) + \sum_{t=2}^T H(X_t | X_1, \dots, X_{t-1}).$$

¹²For more details on entropy and related information theoretic tools, see Cover and Thomas (1991).

Let $(\Omega, \mathcal{F}, \mu)$ be a probability space and let \mathcal{P} be a finite partition of Ω into sets in \mathcal{F} . Then the entropy of the partition \mathcal{P} with respect to μ is defined by

$$H_\mu(\mathcal{P}) = - \sum_{F \in \mathcal{P}} \mu(F) \log_2 \mu(F).$$

It is easy to see that if \mathcal{Q} is a refinement of \mathcal{P} , then $H_\mu(\mathcal{P}) \leq H_\mu(\mathcal{Q})$.

Given a feasible strategy set of player 1, $\Psi_1 \subset \Sigma_1$, we have defined, for each t , the set $\Psi_1(t)$ to be the partition of Ψ_1 induced by an equivalence relation. Specifically, we define an equivalence relation \sim_t by

$$\sigma \sim_t \sigma' \iff \forall \tau \in \Sigma_2, a_s(\sigma, \tau) = a_s(\sigma', \tau) \quad \text{for } s = 1, \dots, t.$$

Then $\Psi_1(t) = \Psi_1 / \sim_t$.

Now fix player 2's strategy τ . Define an equivalence relation $\sim_{t,\tau}$ by

$$\sigma \sim_{t,\tau} \sigma' \iff a_s(\sigma, \tau) = a_s(\sigma', \tau) \quad \text{for } s = 1, \dots, t,$$

and let $\Psi_1(t, \tau) = \Psi_1 / \sim_{t,\tau}$. Clearly $\Psi_1(t, \tau)$ is a finite partition of Ψ_1 , and $\Psi_1(t)$ is a refinement of $\Psi_1(t, \tau)$. Hence, by the property of the entropy of partitions mentioned above,

$$(2) \quad H_\sigma(\Psi_1(t, \tau)) \leq H_\sigma(\Psi_1(t)) \leq \log_2 |\Psi_1(t)| = \log_2 \psi_1(t).$$

By the definition of the equivalence relation defining $\Psi_1(t, \tau)$, each equivalence class $S \in \Psi_1(t, \tau)$ is associated with a history of length t , say $h(S) \in H_t$. More precisely, $h(S)$ is the history of length t which results when the strategy profile (s, τ) is played, for any $s \in S$. Conversely, for any history $h \in H_t$, there is an equivalence class $S \in \Psi_1(t, \tau)$ such that $h = h(S)$. So there is a one-to-one map from $\Psi_1(t, \tau)$ into H_t . Furthermore, the event “a strategy $s \in S \subset \Psi_1(t, \tau)$ is selected by σ ” is equivalent to the event “the history $h(S)$ occurs when (σ, τ) is played.” Therefore,

$$\sigma(S) = P_{\sigma, \tau}(h(S)).$$

Let us write X_1, \dots, X_t for the sequence of action profiles up to stage t when (σ, τ) is played. So it is a random vector with distribution $P_{\sigma, \tau}$. Then the observation in

this paragraph implies that

$$\begin{aligned} H_\sigma(\Psi_1(t, \tau)) &= - \sum_{S \in \Psi_1(t, \tau)} \sigma(S) \log_2 \sigma(S) \\ &= - \sum_{h \in H_t} P_{\sigma, \tau}(h) \log_2 P_{\sigma, \tau}(h) \\ &= H(X_1, \dots, X_t). \end{aligned}$$

Combining this equality with (2) we have

Lemma 2. *Let $\sigma \in \Delta(\Psi_1)$ and $\tau \in \Sigma_2$ and (X_1, \dots, X_t) be the random play up to stage t induced by (σ, τ) . Then, for every t ,*

$$H(X_1, \dots, X_t) \leq \log_2 \psi_1(t).$$

Next, for each mixed action α of player 1, let $H(\alpha)$ be its entropy, i.e.,

$$H(\alpha) = - \sum_{a \in A_1} \alpha(a) \log_2 \alpha(a).$$

Define a function $U : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ by

$$U(\gamma) = \max_{\substack{\alpha \in \Delta(A_1) \\ H(\alpha) \leq \gamma}} \min_{b \in A_2} g(\alpha, b).$$

Thus $U(\gamma)$ is what player 1 can secure in the stage game G using a mixed action of entropy at most γ . Clearly, $U(0) = w$, the maximin payoff in pure actions. On the other hand, $U(\gamma) = v$, the minimax payoff, if $\gamma \geq \bar{\gamma}$ where $\bar{\gamma} = \min \left\{ H(\alpha) : \alpha \in \Delta(A_1), \min_{b \in A_2} g(\alpha, b) = v \right\}$. Let $\text{cav } U$ be the concavification of U , i.e., the smallest concave function which is at least as large as U at every point in its domain.

The function $U(\gamma)$ is strictly increasing and piecewise convex for $0 \leq \gamma \leq \bar{\gamma}$, and then constant, v , for $\gamma \geq \bar{\gamma}$. Thus, for every $\gamma \leq \bar{\gamma}$, there is an $\alpha \in \Delta(A_1)$ such that $H(\alpha) = \gamma$ and $\min_{b \in A_2} g(\alpha, b) = U(\gamma)$. In other words, the entropy constraint defining $U(\gamma)$ is binding for $\gamma \leq \bar{\gamma}$. See Neyman and Okada (2000a) for examples.

The theorem below asserts that, if $\psi_1(t)$ grows like an exponential function $2^{\gamma t}$, then player 1's maximin payoff in the repeated game is at most $(\text{cav } U)(\gamma)$.

Theorem 2. *Suppose that $\overline{\lim}_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} \leq \gamma$. Then, for every $\sigma \in \Delta(\Psi_1)$, there is $\tau \in \Sigma_2$ such that*

$$\overline{\lim}_{T \rightarrow \infty} g_T(\sigma, \tau) \leq (\text{cav } U)(\gamma).$$

Proof: Fix player 1's strategy $\sigma \in \Delta(\Psi_1)$. Define player 2's strategy as follows. At each stage t , and at each history $h \in H_{t-1}$, $\tau(h)$ minimizes player 1's stage payoff, that is,

$$E_{\sigma,\tau}[g(a_t)|h] = \min_{b \in B} E_{\sigma(h)}[g(a, b)].$$

Let X_1, X_2, \dots be the sequence of random actions induced by (σ, τ) . Let $H(X_t|h)$ be the entropy of X_t given that a history h is realized. Note that, conditional on the history h , the entropy of player 1's mixed action at stage t is $H(X_t|h)$. Hence, by the definitions of U , $\text{cav } U$, and τ , we have

$$E_{\sigma,\tau}[g(X_t)|h] \leq U(H(X_t|h)) \leq (\text{cav } U)(H(X_t|h)).$$

Taking the expectation, we have

$$E_{\sigma,\tau}[g(X_t)] \leq E_{\sigma,\tau}[(\text{cav } U)(H(X_t|h))] \leq (\text{cav } U)(E_{\sigma,\tau}[H(X_t|h)])$$

where the second inequality follows from the concavity of $\text{cav } U$ and Jensen's inequality. Summing over $t = 1, \dots, T$ we have

$$\begin{aligned} g_T(\sigma, \tau) &= \frac{1}{T} \sum_{t=1}^T E_{\sigma,\tau}[g(X_t)] \\ &\leq \frac{1}{T} \sum_{t=1}^T (\text{cav } U)(E_{\sigma,\tau}[H(X_t|h)]) \\ &\leq (\text{cav } U) \left(\frac{1}{T} \sum_{t=1}^T E_{\sigma,\tau}[H(X_t|h)] \right) \\ &= (\text{cav } U) \left(\frac{1}{T} \sum_{t=1}^T H(X_t|X_1, \dots, X_{t-1}) \right) \\ &= (\text{cav } U) \left(\frac{1}{T} H(X_1, \dots, X_T) \right) \\ &\leq (\text{cav } U) \left(\frac{\log_2 \psi_1(T)}{T} \right). \end{aligned}$$

The second inequality follows from the concavity of $\text{cav } U$ and Jensen's inequality. The second and the third equalities follow from the definition of conditional entropy and the chain rule respectively. The last inequality follows from Lemma 2. Since $\overline{\lim}_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} \leq \gamma$, we have the desired result. **Q.E.D.**

As in Theorem 1, whether player 1 can achieve $(\text{cav } U)(\gamma)$ or not depends on what strategies are available to him. The next theorem states that there is indeed a

strategy set with an appropriate growth rate with which $(\text{cav } U)(\gamma)$ can be achieved. Furthermore, it states that it suffices to consider oblivious strategies. Combined with Theorem 2, it implies that there is a strategy set Ψ_1 of player 1 consisting only of oblivious strategies for which $\psi_1(t)$ grows like $2^{\gamma t}$ and, relative to which, the maximin value of the repeated game is precisely $(\text{cav } U)(\gamma)$.

Theorem 3. *For every $\gamma \geq 0$ and a function $f : \mathbb{R}_+ \rightarrow [1, \infty)$ with $\frac{\log_2 f(t)}{t} \xrightarrow[t \rightarrow \infty]{} \gamma$, there exists a set of oblivious strategies $\Psi_1 \subset \Sigma_1$ and a mixed strategy $\hat{\sigma} \in \Delta(\Psi_1)$ with the following properties:*

- (i) $\psi_1(t) \leq f(t)$ for every $t \in \mathbb{N}$
- (ii) $\lim_{T \rightarrow \infty} \left(\inf_{\tau \in \Delta(\Sigma_2)} g_T(\hat{\sigma}, \tau) \right) \geq (\text{cav } U)(\gamma)$
- (iii) $\inf_{\tau \in \Delta(\Sigma_2)} \mathbf{E}_{\hat{\sigma}, \tau} \left[\lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T g(a_t, b_t) \right] \geq (\text{cav } U)(\gamma)$

Proof: ¹³ CONSTRUCTION OF Ψ_1 : Recall from Example 2 that, for each sequence $\mathbf{a} = (a_1, a_2, \dots)$ of player 1's pure actions, $\sigma\langle \mathbf{a} \rangle$ denotes his oblivious strategy that takes action a_t at stage t regardless of the past history. We will define a particular class of sequences $F \subset A_1^\infty$ and then set

$$(3) \quad \Psi_1 = \{ \sigma\langle \mathbf{a} \rangle : \mathbf{a} \in F \}.$$

If $\gamma = 0$, then $(\text{cav } U)(\gamma)$ is the maximin payoff in pure actions, w . In this case the set F can be taken as a singleton $\{ \mathbf{a} = (a, a, a, \dots) \}$ where a is any one of player 1's pure actions that guarantees him w .

Suppose that $\gamma > 0$. Recall that $\bar{\gamma} = \min \left\{ H(\alpha) : \alpha \in \Delta(A_1), \min_{b \in A_2} g(\alpha, b) = v \right\}$. As $U(\gamma) = v$ for all $\gamma \geq \bar{\gamma}$, we assume w.l.o.g. that $\gamma \leq \bar{\gamma}$. By modifying $f(t)$ to $\hat{f}(t) = \inf_{s \geq t} f(s)^{t/s}$ if necessary, we will also assume that $\frac{\log_2 f(t)}{t}$ is nondecreasing

¹³The reader will see that the proof presented here makes use of a lemma stated and proved in the appendix. One may wonder, however, whether a different proof not relying on the lemma can be devised. Such a proof, though slightly longer, indeed exists and is presented in the appendix. We have decided to present the proof using the lemma in the main body of this paper because the lemma is used in a crucial way in the proof of Theorem 5 in the next section, and its inclusion here will give a methodological consistency as well as acquaint the reader with how the lemma is used.

in t , or, equivalently,

$$(4) \quad \log_2 f(s) - \log_2 f(t) \geq (s - t) \frac{\log_2 f(t)}{t} \text{ whenever } s > t.$$

In particular, this implies that $f(t)$ is also nondecreasing in t .

In order to construct the set $F \subset A_1^\infty$, we first partition the stages into blocks. Set $t_0 = 0$. The n -th block consists of stages $t_{n-1} + 1$ to t_n . We denote the length of the n -th block by d_n , i.e., $d_n = t_n - t_{n-1}$. Second, we will define for each n a set F_n consisting of finite sequences of player 1's actions of length d_n with certain properties. Then we set F to be those sequences $\mathbf{a} = (a_1, a_2, \dots)$ in A_1^∞ whose n -th segment $\mathbf{a}[n] = (a_{t_{n-1}+1}, \dots, a_{t_n})$ belongs to F_n :

$$(5) \quad F = \{ \mathbf{a} = (a_1, a_2, \dots) \in A_1^\infty : \mathbf{a}[n] = (a_{t_{n-1}+1}, \dots, a_{t_n}) \in F_n \}.$$

Now we describe the construction of the set F_n in detail.

The blocks are chosen so that d_n is increasing, $d_n \xrightarrow[n \rightarrow \infty]{} \infty$, $\frac{d_{n-1}}{d_n} \xrightarrow[n \rightarrow \infty]{} 1$, and thus $\frac{d_n}{t_n} \xrightarrow[n \rightarrow \infty]{} 0$. For example, take $d_n = n$. Next, we construct the sets $(F_n)_n$ by means of a sequence of nonnegative reals, $(\gamma_n)_n$ with $\gamma_n \leq \bar{\gamma}$. The sequence $(\gamma_n)_n$ depends on the function f and will be specified in the last part of the proof. For each n , choose player 1's mixed action α_n so that $H(\alpha_n) = \gamma_n$ and $\min_{b \in A_2} g(\alpha_n, b) = U(\gamma_n)$. (See the remark on the property of U on p.18.)

If $\gamma_n = 0$, then α_n is a pure action, say a^* , that guarantees w . In this case we set F_n to be a singleton consisting of $(a^*, \dots, a^*) \in A^{d_n}$. If $\gamma_n > 0$, then F_n is defined to be the set of all sequences $(a_1, \dots, a_{d_n}) \in A_1^{d_n}$ whose empirical distribution is within $\frac{|A_1|}{d_n}$ of α_n . Formally,

$$(6) \quad F_n = \left\{ (a_1, \dots, a_{d_n}) \in A_1^{d_n} : \sum_{a \in A_1} \left| \frac{1}{d_n} \sum_{k=1}^{d_n} \mathbf{1}(a_k = a) - \alpha_n(a) \right| \leq \frac{|A_1|}{d_n} \right\}.$$

Note that $F_n \neq \emptyset$. We complete this part by defining F by (5) and then Ψ_1 by (3).

CONSTRUCTION OF $\hat{\sigma} \in \Delta(\Psi_1)$: Let $\mathbf{z} = (z_1, z_2, \dots)$ be a sequence of A_1 -valued random variables such that its n -th segment $\mathbf{z}[n] = (z_{t_{n-1}+1}, \dots, z_{t_n})$ is drawn uniformly from F_n , and independently from $\mathbf{z}[1], \dots, \mathbf{z}[n-1]$. Then define $\hat{\sigma} = \sigma\langle \mathbf{z} \rangle$. Observe that $\hat{\sigma}$ is indeed a mixture of strategies in Ψ_1 .

VERIFICATION OF THE THEOREM: From (5) it is clear that we can identify each sequence in the set F with an element of $\prod_{n=1}^{\infty} F_n$ and each strategy in $\Psi_1(t_N)$ with an element in $\prod_{n=1}^N F_n$, $N = 1, 2, \dots$. Hence $\psi_1(t_N) = |\Psi_1(t_N)| = \prod_{n=1}^N |F_n|$ for each $N = 1, 2, \dots$. Since both $\psi_1(t)$ and $f(t)$ are nondecreasing, in order to verify that Ψ_1 has the property (i) of the theorem, it is enough to ensure that¹⁴

$$(7) \quad \sum_{n=1}^N \log_2 |F_n| \leq \log_2 f(t_{N-1}) \quad \text{for each } N > 1.$$

Recall that $|F_n| = 1$ for n with $\gamma_n = 0$. For n with $\gamma_n > 0$ we estimate $|F_n|$ as follows. Each element $\mathbf{a}_n = (a_1, \dots, a_{d_n})$ in F_n has an empirical distribution $\rho(\mathbf{a}_n)$ whose L_1 -distance from α_n is at most $\frac{|A_1|}{d_n}$. Since the entropy $H(\alpha)$ as a function on $\Delta(A_1)$ is uniformly continuous (in the L_1 -distance), there is a nonincreasing sequence of positive reals $(\varepsilon_n)_n$ with $\varepsilon_n \xrightarrow{n \rightarrow \infty} 0$ such that $|H(\rho(\mathbf{a}_n)) - H(\alpha_n)| = |H(\rho(\mathbf{a}_n)) - \gamma_n| < \varepsilon_n$ for all $\mathbf{a}_n \in F_n$. Since the number of distinct empirical distributions arising from sequences in $A_1^{d_n}$ is at most $(d_n + 1)^{|A_1|}$, and the number of sequences in $A_1^{d_n}$ with an empirical distribution α is at most $2^{d_n H(\alpha)}$, we deduce that

$$\frac{1}{(d_n + 1)^{|A_1|}} 2^{d_n(\gamma_n - \varepsilon_n)} \leq |F_n| \leq (d_n + 1)^{|A_1|} 2^{d_n(\gamma_n + \varepsilon_n)}.$$

Setting $\delta_n = \varepsilon_n + |A_1| \frac{\log_2(d_n + 1)}{d_n}$ we have

$$2^{d_n(\gamma_n - \delta_n)} \leq |F_n| \leq 2^{d_n(\gamma_n + \delta_n)}.$$

Note that the sequence $(\delta_n)_{n \geq 2}$ is decreasing and $\delta_n \xrightarrow{n \rightarrow \infty} 0$.

Thus, to ensure that (7) holds, it is enough to choose $(\gamma_n)_n$ so that

$$(8) \quad \sum_{n=1}^N \mathbf{1}(\gamma_n > 0) d_n (\gamma_n + \delta_n) \leq \log_2 f(t_{N-1}) \quad \text{for each } N > 1.$$

Next we derive a sufficient condition to be verified in order to show that $\hat{\sigma}$ has the property (ii). Fix an arbitrary strategy $\tau \in \Sigma_2$. For each $n = 1, 2, \dots$, let $(x_1^{(n)}, y_1^{(n)}), \dots, (x_{d_n}^{(n)}, y_{d_n}^{(n)})$ be the random action pairs induced by $(\hat{\sigma}, \tau)$ in the n -th block. Fix a realization $h_{n-1} \in A^{t_{n-1}}$ of $(x_1^{(1)}, y_1^{(1)}), \dots, (x_{d_{n-1}}^{(n-1)}, y_{d_{n-1}}^{(n-1)})$, i.e., until

¹⁴Observe that (i) asserts that $\psi_1(t) \leq f(t)$ for all t which will be satisfied, as these functions are nondecreasing, if $\psi_1(t_N) \leq f(t_{N-1})$ for each N .

the end of the $(n-1)$ -th block, and let $(\bar{x}^{(n)}, \bar{y}^{(n)})$ be a $(A_1 \times A_2)$ -valued random variable whose distribution is given by

$$\mathbf{P}((\bar{x}^{(n)}, \bar{y}^{(n)}) = (a, b)) := \frac{1}{d_n} \sum_{k=1}^{d_n} \mathbf{P}((x_k^{(n)}, y_k^{(n)}) = (a, b) | h_{n-1}).$$

Then, from (6) and the definition of $\hat{\sigma}$, it easily follows that

$$\sum_{a \in A_1} |\mathbf{P}(\bar{x}^{(n)} = a) - \alpha_n(a)| \leq \frac{|A_1|}{d_n} < \delta_n.$$

Since the conditional entropy $H(X|Y)$ is concave in the joint distribution of (X, Y) (see, e.g., Gossner, Hernandez, and Neyman (2004), Lemma 1), we have

$$\begin{aligned} H(\bar{x}^{(n)} | \bar{y}^{(n)}) &\geq \frac{1}{d_n} \sum_{k=1}^{d_n} H(x_k^{(n)} | y_k^{(n)}, h_{n-1}) \\ &\geq \frac{1}{d_n} \sum_{k=1}^{d_n} H(x_k^{(n)} | y_k^{(n)}, h_{n-1}, x_1^{(n)}, \dots, x_{k-1}^{(n)}) \\ &= \frac{1}{d_n} \sum_{k=1}^{d_n} H(x_k^{(n)} | h_{n-1}, x_1^{(n)}, \dots, x_{k-1}^{(n)}) \end{aligned}$$

where the last equality holds due to the fact that τ is a pure strategy and hence $y_k^{(n)}$ is a deterministic function of h_{n-1} and $x_1^{(n)}, \dots, x_{k-1}^{(n)}$. Using the chain rule for entropy, and since, conditional on h_{n-1} , the string $(z_{t_{n-1}+1}, \dots, z_{t_n})$ is chosen uniformly from F_n , the last expression above is equal to

$$\frac{H(x_1^{(n)}, \dots, x_{d_n}^{(n)} | h_{n-1})}{d_n} = \frac{H(z_{t_{n-1}+1}, \dots, z_{t_n} | h_{n-1})}{d_n} = \frac{\log_2 |F_n|}{d_n} \geq \gamma_n - \delta_n.$$

As $\gamma_n = H(\alpha_n)$, we conclude that

$$(9) \quad H(\bar{x}^{(n)} | \bar{y}^{(n)}) > H(\alpha_n) - \delta_n.$$

By Lemma 3 (in the appendix) there is a function $\eta : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, which depends on the stage game, with $\eta(\delta) \xrightarrow{\delta \rightarrow 0} 0$ such that if (x, y) is a $(A_1 \times A_2)$ -valued random variable satisfying (i) $H(x|y) \geq H(\alpha^*) - \delta$ and (ii) $\sum_{a \in A_1} |\mathbf{P}(x = a) - \alpha^*(a)| < \delta$, then $\mathbf{E}[g(x, y)] \geq \min_{b \in A_2} g(\alpha^*, b) - \eta(\delta)$. Thus, the inequalities (??) and (9) imply that there is a function $\eta : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ with $\eta(\delta) \xrightarrow{\delta \rightarrow 0} 0$ such that

$$\mathbf{E} \left[\frac{1}{d_n} \sum_{k=1}^{d_n} g(x_k^{(n)}, y_k^{(n)}) \Big| h_{n-1} \right] = \mathbf{E} [g(\bar{x}^{(n)}, \bar{y}^{(n)}) | h_{n-1}] \geq U(\gamma_n) - \eta(\delta_n).$$

Recall that $\min_{b \in A_2} g(\alpha_n, b) = U(\gamma_n)$. As this holds for any τ , n , and h_{n-1} , it follows that, for any $N = 1, 2, \dots$,

$$\min_{\tau \in \Sigma_2} g_{t_N}(\hat{\sigma}, \tau) = \frac{1}{t_N} \sum_{n=1}^N \mathbf{E} \left[\sum_{k=1}^{d_n} g(x_k^{(n)}, y_k^{(n)}) \right] \geq \frac{1}{t_N} \sum_{n=1}^N d_n U(\gamma_n) - \frac{1}{t_N} \sum_{n=1}^N d_n \eta(\delta_n).$$

Since $t_N = \sum_{n=1}^N d_n$ and $\eta(\delta_n) \xrightarrow{n \rightarrow \infty} 0$, the second term on the right side converges to 0 as $N \rightarrow \infty$. In addition, recall that $\frac{d_N}{t_N} \xrightarrow{N \rightarrow \infty} 0$. Hence, in order to show part (ii) of the theorem, it suffices to choose $(\gamma_n)_n$ so that

$$(10) \quad \frac{1}{t_N} \sum_{n=1}^N d_n U(\gamma_n) \xrightarrow{N \rightarrow \infty} (\text{cav } U)(\gamma).$$

We now exhibit a choice of $(\gamma_n)_n$ that satisfies (7) and (10). We distinguish two cases.

CASE 1 - $(\text{cav } U)(\gamma) = U(\gamma)$: From the assumption $\frac{d_{n-1}}{d_n} \xrightarrow{n \rightarrow \infty} 1$, it follows that $\frac{d_{n-1} \log_2 f(t_{n-1})}{d_n t_{n-1}} \xrightarrow{n \rightarrow \infty} \gamma > 0$. As $\delta_n \xrightarrow{n \rightarrow \infty} 0$, there is an \bar{n} such that $\frac{d_{n-1} \log_2 f(t_{n-1})}{d_n t_{n-1}} > \delta_n$ for all $n > \bar{n}$. For $n \leq \bar{n}$, set $\gamma_n = 0$, and, for $n > \bar{n}$, let $\gamma_n = \frac{d_{n-1} \log_2 f(t_{n-1})}{d_n t_{n-1}} - \delta_n$. With this choice of $(\gamma_n)_n$ it is easy to verify that (8), and hence (7), is satisfied. Since $\gamma_n \xrightarrow{n \rightarrow \infty} \gamma$, the condition (10) is satisfied as well.

CASE 2 - $(\text{cav } U)(\gamma) > U(\gamma)$: In this case, the definitions of U and $\text{cav } U$ imply the existence of γ_-, γ_+ with $0 \leq \gamma_- < \gamma < \gamma_+$ and $\alpha_-, \alpha_+ \in \Delta(A_1)$ together with a $p \in (0, 1)$ such that

- a) $\gamma = p\gamma_- + (1-p)\gamma_+$
- b) $(\text{cav } U)(\gamma) = pU(\gamma_-) + (1-p)U(\gamma_+)$
- c) $H(\alpha_-) = \gamma_-$ and $H(\alpha_+) = \gamma_+$
- d) $g(\alpha_-, b) \geq U(\gamma_-)$ and $g(\alpha_+, b) \geq U(\gamma_+)$ for all $b \in A_2$.

Choose \bar{n} large enough so that for $n \geq \bar{n}$ we have $\frac{d_{n-1} \log_2 f(t_{n-2})}{d_n t_{n-2}} - \delta_n > \gamma_-$. Set $\gamma_n = 0$ for $n \leq \bar{n}$ and, for $n > \bar{n}$, define γ_n by induction as follows:

$$\gamma_n = \begin{cases} \gamma_+ & \text{if } \sum_{\ell=1}^{n-1} 1(\gamma_\ell > 0) d_\ell (\gamma_\ell + \delta_\ell) + d_n (\gamma_+ + \delta_n) \leq \log_2 f(t_{n-1}), \\ \gamma_- & \text{otherwise.} \end{cases}$$

With the above choice of the sequence $(\gamma_n)_n$, we have $|F_n| = 1$ for $n \leq \bar{n}$. So for $N \leq \bar{n}$, the inequality (7) trivially holds. For $N > \bar{n}$, inequality (8) is proved by induction. Assume that $\sum_{\ell=1}^{N-1} 1(\gamma_\ell > 0)d_\ell(\gamma_\ell + \delta_\ell) \leq \log_2 f(t_{N-2})$. Then,

$$\begin{aligned} \sum_{\ell=1}^{N-1} 1(\gamma_\ell > 0)d_\ell(\gamma_\ell + \delta_\ell) + d_N(\gamma_- + \delta_N) &\leq \log_2 f(t_{N-2}) + d_{N-1} \frac{\log_2 f(t_{N-2})}{t_{N-2}} \\ &\leq \log_2 f(t_{N-1}) \end{aligned}$$

where the first inequality holds by the induction hypothesis and since $N > \bar{n}$, while the second inequality follows from (4). Therefore, if $\gamma_N = \gamma_-$ then inequality (8) holds for N . Obviously, by the definition of γ_N , if $\gamma_N = \gamma_+$ then inequality (8) again holds for N . We conclude that inequality (8), hence (7), holds for all $N > \bar{n}$.

Since $\gamma_n = \gamma_-$ or γ_+ for all $n > \bar{n}$, in order to show (10), it suffices to verify that

$$(11) \quad \frac{1}{t_N} \sum_{n=\bar{n}+1}^N d_n \mathbf{1}(\gamma_n = \gamma_-) \xrightarrow{N \rightarrow \infty} p.$$

For each N let $M_N = \max\{n \leq N : \gamma_n = \gamma_-\}$. Note that $M_N \rightarrow \infty$ as $N \rightarrow \infty$ since $\gamma_+ > \gamma_-$. Since $\frac{\log_2 f(t_{n-1})}{t_n} = \left(1 - \frac{d_n}{t_n}\right) \frac{\log_2 f(t_{n-1})}{t_{n-1}} \xrightarrow{n \rightarrow \infty} \gamma$, we have, for every $\delta > 0$, an N such that $\frac{\log_2 f(t_{n-1})}{t_n} \geq \gamma - \delta$ for all $n \geq M_N$. Hence

$$\begin{aligned} &\sum_{n=1}^N 1(\gamma_n > 0)d_n(\gamma_n + \delta_n) \\ &= \sum_{n=1}^{M_N} 1(\gamma_n > 0)d_n(\gamma_n + \delta_n) + \sum_{n=M_N+1}^N 1(\gamma_n > 0)d_n(\gamma_n + \delta_n) \\ &\geq \log_2 f(t_{M_N-1}) - d_{M_N}(\gamma_+ - \gamma_-) + (t_N - t_{M_N})\gamma_+ \\ &\geq t_{M_N}(\gamma - \delta) - d_N(\gamma_+ - \gamma_-) + (t_N - t_{M_N})\gamma \\ &\geq t_N(\gamma - \delta) - d_N(\gamma_+ - \gamma_-). \end{aligned}$$

Since $\sum_{n=1}^N 1(\gamma_n > 0)d_n(\gamma_n + \delta_n) \leq \log f(t_{N-1})$, $\delta_n \xrightarrow{n \rightarrow \infty} 0$, and $\frac{d_N}{t_N} \xrightarrow{N \rightarrow \infty} 0$, we conclude that $\frac{1}{t_N} \sum_{n=1}^N d_n \gamma_n \xrightarrow{N \rightarrow \infty} \gamma$, which implies (11).

Finally we will verify that $\hat{\sigma}$ has the property (iii). By the same argument as in pp.21-23, one can show that, for every $\tau \in \Sigma_2$,

$$\sum_{n=1}^N \mathbf{E}_{\hat{\sigma}, \tau} \left[\sum_{k=1}^{d_n} g(x_k^{(m+n)}, y_k^{(m+n)}) \middle| h_m \right] \geq \sum_{n=1}^N d_{m+n} U(\gamma_{m+n}) - \sum_{n=1}^N d_{m+n} \eta(\delta_{m+n})$$

holds for every m and $h_m \in A^{t_m}$. The analysis of CASE 1 and CASE 2 above (performed conditional on h_m) together with a classical result in probability theory implies that, for any $\tau \in \Sigma_2$,

$$\underline{\lim}_{N \rightarrow \infty} \frac{1}{t_N} \sum_{n=1}^N \sum_{k=1}^{d_n} g(x_k^{(n)}, y_k^{(n)}) \geq (\text{cav } U)(\gamma) \quad \text{almost surely}$$

from which (iii) readily follows. **Q.E.D.**

Remark 3.1. An additional property of ψ_1 constructed in the above proof is that $\lim_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} = \gamma$. Although this can be verified by examining the details of the proof, an alternative derivation of it illuminates a connection between the growth of strategy set and entropy.

On the one hand, the property (i) in Theorem 3 implies that $\overline{\lim}_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} \leq \gamma$. On the other hand, the property (ii) and our previously published result on strategic entropy (Neyman and Okada (2000a)) imply that $\underline{\lim}_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} \geq \gamma$. To see this, let us recall that the t -strategic entropy of player 1's strategy σ is defined by $H^t(\sigma) = \max_{\tau \in \Sigma_2} H(X_1, \dots, X_t)$ where X_1, \dots, X_t is the random sequence of action profiles induced by (σ, τ) . Lemma 2 in Section 3.2 then implies that $H^T(\sigma) \leq \log_2 \psi_1(T)$ for all $\sigma \in \Delta(\Psi_1)$ and T . This, together with Theorem 5.1 of Neyman and Okada (2000a), implies that

$$\inf_{\tau \in \Sigma_2} g_T(\sigma, \tau) \leq (\text{cav } U) \left(\frac{\log_2 \psi_1(T)}{T} \right)$$

for all $\sigma \in \Delta(\Psi_1)$ and T . Thus, if $\underline{\lim}_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} < \gamma$, then $\underline{\lim}_{T \rightarrow \infty} \left(\inf_{\tau \in \Sigma_2} g_T(\sigma, \tau) \right) < (\text{cav } U)(\gamma)$, contradicting property (ii) of Theorem 3. Hence we conclude that $\lim_{t \rightarrow \infty} \frac{\log_2 \psi_1(t)}{t} = \gamma$.

4. NONSTATIONARY BOUNDED RECALL STRATEGIES

In this section, we study a concrete case of the game examined in the last section. Specifically, player 1's feasible strategy set is taken to be $\mathbf{B}_1(\kappa) = \{\sigma \wedge \kappa : \sigma \in \Sigma_1\}$, the set of κ -recall strategies. Player 2 is assumed to have full recall. Let $G^*(\kappa)$ be the repeated game under consideration and let $V(\kappa)$ be player 1's minimax payoff in $G^*(\kappa)$. The results in this section characterize $V(\kappa)$ in terms of asymptotic

behavior of the recall function κ . We will also discuss a folk theorem in repeated games with nonstationary bounded recall strategies at the end of the section.

Recall that, with $\Psi_1 = \mathbf{B}_1(\kappa)$, we have $\log_2 \psi_1(t) \leq c m^{\bar{\kappa}(t)}$ for a constant c (e.g., $c = m/(m-1)$) where $\bar{\kappa}(t) = \max_{s \leq t} \kappa(s)$. Suppose that, for every $\varepsilon > 0$, we have $\kappa(t) < (1-\varepsilon) \frac{\log_2 t}{\log_2 m}$ for sufficiently large t . Then it follows that¹⁵ $\frac{\log_2 \psi_1(t)}{t} \xrightarrow{t \rightarrow \infty} 0$. Hence, by Theorem 1 together with the fact that player 1 can always guarantee $w = \max_{a \in A_1} \min_{a_2 \in A_2} g(a, a_2)$ with a stationary bounded recall strategy of size 0, we obtain the following result.

Theorem 4. *If $\overline{\lim}_{t \rightarrow \infty} \frac{\kappa(t)}{\log_2 t} < \frac{1}{\log_2 m}$, then $V(\kappa) = w$.*

This suggests that, in order to gain any benefit from recalling the past (to get a payoff above w) against a player with perfect recollection, one must remember at least some constant times $\log_2 t$ stages back. It is thus natural to ask, ‘‘How fast should κ grow (asymptotically) in order to guarantee the minimax payoff v against a player with full recall?’’ This question will be answered in the next theorem. It asserts that, in order to secure v in the long run, it suffices that player 1’s recall $\kappa(t)$ grows at least as fast as $K_1 \log_2 t$ for some $K_1 > 0$. (Of course, $K_1 \geq 1/\log_2 m$.) In particular, player 1 can guarantee the minimax payoff in the long run by recalling a vanishing fraction of the history even against a player with full recall.

In order to exhibit the constant K_1 explicitly, let $\zeta(G) = \max_{\alpha} \max_{a \in A_1} \alpha(a)$ where α is taken over all mixed actions of player 1 in the stage game G with $\min_{b \in A_2} g(\alpha, b) = v$. For example, $\zeta(G) = 1$ if the minimax payoff v can be secured by a pure action. Define

$$K_1(G) = \begin{cases} 0 & \text{if } \zeta(G) = 1, \\ \frac{2}{|\log_2 \zeta(G)|} & \text{if } \zeta(G) < 1. \end{cases}$$

For instance, in matching pennies, $\zeta(G) = 1/2$ and so $K_1(G) = 2$.

Theorem 5. *If $\overline{\lim}_{t \rightarrow \infty} \frac{\kappa(t)}{\log_2 t} > K_1(G)$, then there is a $\hat{\sigma} \in \Delta(\mathbf{B}_1(\kappa))$ with the following properties:*

$$(i) \quad \overline{\lim}_{T \rightarrow \infty} \left(\min_{\tau \in \Sigma_2} g_T(\hat{\sigma}, \tau) \right) \geq v,$$

¹⁵For the conclusion it suffices to have $\kappa(t) < \frac{\log_2 t}{\log_2 m} - c(t)$ where $c(t) \xrightarrow{t \rightarrow \infty} \infty$.

$$(ii) \quad \inf_{\tau \in \Sigma_2} \mathbf{E}_{\hat{\sigma}, \tau} \left[\liminf_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T g(a_t, b_t) \right] \geq v.$$

In particular, if G is zero-sum, then the repeated game $G^*(\kappa)$ has the value¹⁶ equal to the value of G . Moreover, player 1 has an optimal strategy $\hat{\sigma} \in \Delta(\mathbf{B}_1(\kappa))$.

Proof: Let $\alpha^* \in \Delta(A_1)$ be such that $\min_{b \in A_2} g(\alpha^*, b) = v$ and $\max_{a \in A_1} \alpha^*(a) = \zeta(G)$. If α^* is a pure action, then the theorem is trivially true. So suppose that α^* is not a pure action. Then there are two distinct actions $a^0, a^1 \in A_1$ with $\alpha^*(a^0) > 0$ and $\alpha^*(a^1) > 0$.

In order to define the strategy $\hat{\sigma}$, we introduce some notation. First, our condition on κ implies that there are infinitely many stages t at which $\kappa(t) \neq \kappa(s)$ for all $s < t$. We enumerate these stages as $t_1 < t_2 < \dots < t_n < \dots$. For each sequence of player 1's actions $\mathbf{a} = (a_1, a_2, \dots) \in A_1^\infty$ and each positive integer n , define a sequence $\mathbf{a}^n = (a_1^n, a_2^n, \dots) \in A_1^\infty$ by

$$a_t^n = \begin{cases} a^0 & \text{if } t < t_n, \\ a^1 & \text{if } t = t_n, \\ a_t & \text{if } t > t_n. \end{cases}$$

Thus, if player 1 is to play according to the oblivious strategy $\sigma(\mathbf{a}^n)$, he will take the action a^0 in the first $t_n - 1$ stages, then a^1 at stage t_n , and thereafter the actions appearing in the original sequence \mathbf{a} .

Suppose that the sequence \mathbf{a} satisfies the following property for some n .

$$(12) \quad \forall t, t' \text{ s.t. } a_t^n \neq a_{t'}^n : (a_{t'-\kappa(t')}, \dots, a_{t'-1}^n) \neq (a_{t-\kappa(t)}, \dots, a_{t-1}^n).$$

Thus the sequence of actions \mathbf{a}^n is induced by the κ -recall (oblivious) strategy $\sigma(\mathbf{a}^n) \wedge \kappa$. It follows from the definition of the sequence \mathbf{a}^n that, for all t and t' with $t_n \leq t < t'$ and $t' - \kappa(t') < t_n$, we have $(a_{t'-\kappa(t')}, \dots, a_{t'-1}^n) \neq (a_{t-\kappa(t)}, \dots, a_{t-1}^n)$. In addition, since $\kappa(t_n) \neq \kappa(t)$ for all $t < t_n$, the condition (12) is implied by

$$(13) \quad \forall t' \text{ s.t. } t' - \kappa(t') > t_n \forall t < t' : (a_{t'-\kappa(t')}, \dots, a_{t'-1}^n) \neq (a_{t-\kappa(t)}, \dots, a_{t-1}^n).$$

¹⁶The zero-sum game $G^*(\kappa)$ has a value v if for every $\varepsilon > 0$ there are strategies σ_ε^* and τ_ε^* (ε -optimal strategies) such that for all sufficiently large T and for all strategies σ and τ we have $g_T(\sigma_\varepsilon^*, \tau) \geq v - \varepsilon$ and $g_T(\sigma, \tau_\varepsilon^*) \leq v + \varepsilon$. A strategy is optimal if it is ε -optimal for all $\varepsilon > 0$.

Observe that, for any n, t , and k , $(a_{t-k}^n, \dots, a_{t-1}^n)$ is one of at most $k+2$ strings of length k : (a^0, \dots, a^0) , (a^0, \dots, a^0, a^1) , $(a^0, \dots, a^0, a^1, a_{t-\ell}, \dots, a_{t-1})$ where $1 \leq \ell \leq k-2$, $(a^1, a_{t-k+1}, \dots, a_{t-1})$, and $(a_{t-k}, \dots, a_{t-1})$. Let us denote the subset of A_1^k consisting of these strings by $Z(a_{t-k}, \dots, a_{t-1})$ so that (13), hence (12), is further implied by

$$(14) \quad \forall t' \text{ s.t. } t' - \kappa(t') > t_n \quad \forall t < t' : (a_{t'-\kappa(t')}, \dots, a_{t'-1}) \notin Z(a_{t-\kappa(t)}, \dots, a_{t-1}).$$

To formally define the strategy $\hat{\sigma}$, let $\mathbf{z} = (z_1, z_2, \dots)$ be a sequence of A_1 -valued i.i.d. r.v.'s with $z_t \sim \alpha^*$, and, for each n , define a sequence of A_1 -valued r.v.'s $\mathbf{z}^n = (z_1^n, z_2^n, \dots)$ by

$$z_t^n = \begin{cases} a^0 & \text{if } t < t_n, \\ a^1 & \text{if } t = t_n, \\ z_t & \text{if } t > t_n. \end{cases}$$

Next define an \mathbb{N} -valued r.v. ν by $\nu = n$ if n is the smallest positive integer with the property

$$(15) \quad \forall t' \text{ s.t. } t' - \kappa(t') > t_n, \quad \forall t < t' : (z_{t'-\kappa(t')}, \dots, z_{t'-1}) \notin Z(z_{t-\kappa(t)}, \dots, z_{t-1}).$$

Then define $\hat{\sigma} = \sigma\langle \mathbf{z}^\nu \rangle \wedge \kappa$. Below we will show that $\nu < \infty$ almost surely under the condition on $\kappa(t)$ stated in the theorem, and hence $\hat{\sigma}$ is well defined as a mixture of strategies in $\{\sigma\langle \mathbf{a}^n \rangle \wedge \kappa : \mathbf{a} \in A_1^\infty, n = 1, 2, \dots\} \subset \mathbf{B}_1(\kappa)$.

To see this, observe that

$$\begin{aligned} & \mathbf{E} \left[\left| \left\{ (t, t') : t < t', (z_{t'-\kappa(t')}, \dots, z_{t'-1}) \in Z(z_{t-\kappa(t)}, \dots, z_{t-1}) \right\} \right| \right] \\ &= \mathbf{E} \left[\sum_{k=1}^{\infty} \sum_{t < t'} \mathbf{1}(\kappa(t) = \kappa(t') = k) \mathbf{1}((z_{t'-k}, \dots, z_{t'-1}) \in Z(z_{t-k}, \dots, z_{t-1})) \right] \\ &= \sum_{k=1}^{\infty} \sum_{t < t'} \mathbf{1}(\kappa(t) = \kappa(t') = k) \mathbf{P}((z_{t'-k}, \dots, z_{t'-1}) \in Z(z_{t-k}, \dots, z_{t-1})) \\ &\leq \sum_{k=1}^{\infty} (k+2) |B_k|^2 \zeta(G)^k \quad (\text{where } B_k = \{t : \kappa(t) = k\}) \\ &\leq 2 \sum_{t=1}^{\infty} t(\kappa(t) + 2) \zeta(G)^{\kappa(t)}. \end{aligned}$$

For the second-to-the-last inequality, we used the fact that $|Z(z_{t-k}, \dots, z_{t-1})| \leq k+2$, as observed above. The last inequality follows from the inequality $|B_k|^2 <$

$2 \sum_{t \in \mathcal{B}_k} t$. Our condition on κ implies that there is an $\varepsilon > 0$ and a \hat{t} such that $\kappa(t) \geq (K_1(G) + 2\varepsilon) \log_2 t$ for all $t \geq \hat{t}$. Therefore there is a $0 < \theta < 1$ and a $\tilde{t} \geq \hat{t}$ such that $\theta\kappa(t) \geq (K_1(G) + \varepsilon) \log_2 t$ and $(\kappa(t) + 2)\zeta(G)^{(1-\theta)\kappa(t)} < 1$ for all $t \geq \tilde{t}$. As $\zeta(G) < 1$, it follows that $t(\kappa(t) + 2)\zeta(G)^{\kappa(t)} \leq t^{-(1+\varepsilon|\log_2 \zeta(G)|)}$ for all $t \geq \tilde{t}$. Hence $\sum_{t=1}^{\infty} t(\kappa(t) + 2)\zeta(G)^{\kappa(t)} < \infty$. Therefore, with probability 1, there are only finitely many pairs (t, t') with $t < t'$ and $(z_{t'-\kappa(t)}, \dots, z_{t'-1}) \in Z(z_{t-\kappa(t)}, \dots, z_{t-1})$. Thus $\nu < \infty$ almost surely.

Next we verify that $\hat{\sigma}$ has the desired properties. Fix an arbitrary pure strategy $\tau \in \Sigma_2$ and a stage T . Let $(x_1, y_1), \dots, (x_T, y_T)$ be the random action pairs induced by $(\hat{\sigma}, \tau)$. Let (\bar{x}_T, \bar{y}_T) be a $(A_1 \times A_2)$ -valued random variable such that $\mathbb{P}((\bar{x}_T, \bar{y}_T) = (a, b)) = \frac{1}{T} \sum_{t=1}^T \mathbb{P}((x_t, y_t) = (a, b))$. Then, as in the proof of Theorem 3, we have

$$\begin{aligned}
 H(\bar{x}_T | \bar{y}_T) &\geq \frac{1}{T} \sum_{t=1}^T H(x_t | y_t) \geq \frac{1}{T} \sum_{t=1}^T H(x_t | y_t, x_1, \dots, x_{t-1}) \\
 (16) \qquad &= \frac{1}{T} \sum_{t=1}^T H(x_t | x_1, \dots, x_{t-1}) \\
 &\geq \frac{1}{T} \sum_{t=1}^T H(x_t | x_1, \dots, x_{t-1}, t_\nu \wedge (T+1))
 \end{aligned}$$

where the equality follows from y_t being a deterministic function of x_1, \dots, x_{t-1} .

Observe that $z_t \in A_1$ and thus a conditional entropy of z_t is bounded by $\log_2 |A_1|$, and, conditional on $t_\nu < t$, we have $z_t = z_t' = x_t$. Therefore, $H(z_t | z_1, \dots, z_{t-1}, t_\nu \wedge (T+1)) \leq H(x_t | x_1, \dots, x_{t-1}, t_\nu \wedge (T+1)) + \log_2 |A_2| \mathbb{P}(t \leq t_\nu)$. By rearranging the terms we have

$$H(x_t | x_1, \dots, x_{t-1}, t_\nu \wedge (T+1)) \geq H(z_t | z_1, \dots, z_{t-1}, t_\nu \wedge (T+1)) - \log_2 |A_1| \mathbb{P}(t \leq t_\nu).$$

From the chain of inequalities beginning (16), and further applying the chain rule for entropy, and, using the fact that $t_\nu \wedge (T+1)$ takes at most $T+1$ distinct values,

we obtain

$$\begin{aligned}
H(\bar{x}_T|\bar{y}_T) &\geq \frac{1}{T} \sum_{t=1}^T H(z_t|z_1, \dots, z_{t-1}, t_\nu \wedge (T+1)) - \frac{1}{T} \sum_{t=1}^T \log_2 |A_1| \mathbb{P}(t \leq t_\nu) \\
&= \frac{1}{T} H(z_1, \dots, z_T | t_\nu \wedge (T+1)) - \frac{1}{T} \sum_{t=1}^T \log_2 |A_1| \mathbb{P}(t \leq t_\nu) \\
&\geq \frac{1}{T} H(z_1, \dots, z_T) - \frac{1}{T} \log_2(T+1) - \frac{1}{T} \sum_{t=1}^T \log_2 |A_1| \mathbb{P}(t \leq t_\nu) \\
&= H(\alpha^*) - o(1) \xrightarrow{T \rightarrow \infty} H(\alpha^*).
\end{aligned}$$

Note that the $o(1)$ function in the last line is independent of τ . To summarize, for every $\delta > 0$, there is a T_0 such that, for every $T \geq T_0$ and $\tau \in \Sigma_2$, the average empirical distribution of action pairs in the first T stages of the game (i.e., the distribution of (\bar{x}_T, \bar{y}_T)) obeys

$$(17) \quad H(\bar{x}_T|\bar{y}_T) \geq H(\alpha^*) - \delta.$$

Next we demonstrate that the distribution of \bar{x}_T is close to α^* . Since $x_t = z_t$ whenever $t_\nu < t$, we have, for each $a \in A_1$,

$$\mathbb{P}(x_t = a) \geq \mathbb{P}(z_t = a) - \mathbb{P}(t_\nu \geq t) = \alpha^*(a) - \mathbb{P}(t_\nu \geq t)$$

and so $\sum_{a \in A_1} |\mathbb{P}(x_t = a) - \alpha^*(a)| \leq 2|A_1| \mathbb{P}(t_\nu \geq t)$. Hence

$$\begin{aligned}
\sum_{a \in A_1} |\mathbb{P}(\bar{x}_T = a) - \alpha^*(a)| &= \sum_{a \in A_1} \left| \frac{1}{T} \sum_{t=1}^T \mathbb{P}(x_t = a) - \alpha^*(a) \right| \\
&\leq 2|A_1| \frac{1}{T} \sum_{t=1}^T \mathbb{P}(t_\nu \geq t) \xrightarrow{T \rightarrow \infty} 0.
\end{aligned}$$

Thus, for every $\delta > 0$ there is a T_0 such that for all $T \geq T_0$ we have

$$(18) \quad \sum_{a \in A_1} |\mathbb{P}(\bar{x}_T = a) - \alpha^*(a)| < \delta.$$

Hence, by Lemma 3, the inequalities (17) and (18) imply that, for every $\varepsilon > 0$ there is a T_0 such that for all $T \geq T_0$,

$$g_T(\hat{\sigma}, \tau) = \frac{1}{T} \sum_{t=1}^T \mathbf{E}_{\hat{\sigma}, \tau} [g(x_t, y_t)] = \mathbf{E}_{\hat{\sigma}, \tau} [g(\bar{x}_T, \bar{y}_T)] \geq \min_{b \in A_2} g(\alpha^*, b) - \varepsilon = v - \varepsilon.$$

This completes the first part of the theorem.

In order to deduce the second part, observe that, by performing the same line of argument as above but conditional on a history $(x_1, y_1, \dots, x_s, y_s)$, we can show that for every $\varepsilon > 0$ there is a T_0 such that for every strategy $\tau \in \Sigma_2$, every positive integer s , and every $T \geq T_0$, we have

$$\mathbf{E}_{\hat{\sigma}, \tau} \left[\frac{1}{T} \sum_{t=s+1}^{s+T} g(x_t, y_t) \middle| x_1, y_1, \dots, x_s, y_s \right] \geq v - \varepsilon,$$

which, by the classical results in probability, implies that

$$\liminf_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T g(x_t, y_t) \geq v - \varepsilon \quad \text{almost surely.}$$

As this holds for every $\varepsilon > 0$ the second part of the theorem follows. **Q.E.D.**

Remark 4.1. The strategy $\hat{\sigma}$ constructed in the above proof relies on the random variable ν which depends on the values of the entire sequence $(z_t)_t$. (In particular, ν is not a stopping time.) A slightly weaker result can be derived as follows.

Since $\nu < \infty$ almost surely, we have $P(\nu \leq n) \xrightarrow{n \rightarrow \infty} 1$. Hence if we choose an n sufficiently large, the condition (15) holds with a probability close to 1. Therefore, for every $\varepsilon > 0$, there is an n and a T_0 such that for every $\tau \in \Sigma_2$ and $T \geq T_0$, we have $g_T(\sigma(\mathbf{z}^n), \tau) > v - \varepsilon$. In the case where G is a zero-sum game, this shows that, for every $\varepsilon > 0$, the strategy $\sigma(\mathbf{z}^n)$ is ε -optimal for a sufficiently large n .

To conclude this section we discuss an implication of Theorem 5 for the set of equilibrium payoff vectors. Consider the repeated game $G^*(\kappa_1, \kappa_2)$ where player i 's set of feasible strategies is $\mathbf{B}_i(\kappa_i)$, $i = 1, 2$. Define $K_2(G)$ analogously to $K_1(G)$ above. If $\liminf_{t \rightarrow \infty} \frac{\kappa_i(t)}{\log_2 t} > K_i(G)$ for $i = 1, 2$, then Theorem 5, or the strategy constructed in its proof, provides the players with threats to one another which discourage them from deviating from a path¹⁷ that yields $x_i \geq v_i$, $i = 1, 2$. In order to state a version of the folk theorem in this context, let $E^*(\kappa_1, \kappa_2)$ be the set of equilibrium payoff vectors of $G^*(\kappa_1, \kappa_2)$ and let $F^* = \{(x_1, x_2) \in \text{co}(g(A)) : x_1 \geq v^1, x_2 \geq v^2\}$.

¹⁷Specifically, let ξ be a sequence of action pairs that yields an average payoff vector as close to (x_1, x_2) as one desires. Then we can let the players play a constant action pair (\bar{a}, \bar{b}) at each stage until their recall is long enough, and then start the cyclic play of ξ . Thus it can be ensured that any deviation by one player from cooperative phase will be in the memory of the other player long enough to initiate and continue the punishment strategy.

Theorem 6. *There is a constant $K^*(G) > 0$ (that depends on the stage game) such that if $\liminf_{t \rightarrow \infty} \min_{i=1,2} \frac{\kappa_i(t)}{\log_2 t} > K^*(G)$, then $E^*(\kappa_1, \kappa_2) = F^*$.*

APPENDIX I

Here we will prove a statement used in the proof of Theorem 3 and Theorem 5. Recall that the L_1 -distance between two probabilities P and Q on a finite set Ω is $\|P - Q\|_1 = \sum_{x \in \Omega} |P(x) - Q(x)|$. For a $(A_1 \times A_2)$ -valued random variable (x, y) , we write $P(a, b)$ for $P(x = a, y = b)$, and $P_1(a)$ (resp. $P_2(b)$) for $P(x = a)$ (resp. $P(y = b)$). Also, $P_1 \otimes P_2$ is a probability on $A_1 \times A_2$ with $(P_1 \otimes P_2)(a, b) = P_1(a)P_2(b)$ for each $(a, b) \in A_1 \times A_2$.

Lemma 3. *There exists a function $\eta : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, which depends on the stage game, with the following properties:*

- (1) $\eta(\delta) \xrightarrow{\delta \rightarrow 0} 0$.
- (2) For any $\alpha \in \Delta(A_1)$ and for any $(A_1 \times A_2)$ -valued random variable (x, y) satisfying (i) $H(x|y) \geq H(\alpha) - \delta$ and (ii) $\|P_1 - \alpha\|_1 < \delta$, we have $\mathbf{E}[g(x, y)] \geq \min_{b \in A_2} g(\alpha, b) - \eta(\delta)$.

Proof: We will show that, for small $\delta > 0$, (i) and (ii) imply that x and y are nearly independent, or, more precisely, P is close to $P_1 \otimes P_2$ in the L_1 -distance. As the expected payoff is continuous with respect to the L_1 -distance on $\Delta(A_1 \times A_2)$, the conclusion of the lemma follows.

So suppose that (i) and (ii) are satisfied for a $\delta > 0$. Then, since conditioning reduces entropy, (i) implies that $H(x) \geq H(x|y) \geq H(\alpha) - \delta$. Next, since H , as a function on $\Delta(A_1)$, is uniformly continuous with respect to the L_1 -norm, (ii) implies that $H(x) \leq H(\alpha) + \theta(\delta)$ where¹⁸ $\theta(\delta) > 0$ and $\theta(\delta) \xrightarrow{\delta \rightarrow 0} 0$. Thus

$$(19) \quad H(x) - H(x|y) \leq \theta(\delta) + \delta.$$

Let us recall that the relative entropy between two probabilities P and Q on $A_1 \times A_2$ is defined by $D(P\|Q) = \sum_{a,b} P(a, b) \log_2 \frac{P(a, b)}{Q(a, b)}$ where, for any $p, q > 0$, we set $0 \log_2 \frac{0}{q} \equiv 0$ and $p \log_2 \frac{p}{0} \equiv \infty$. The relative entropy is always nonnegative and equal to 0 if, and only if, $P = Q$. From this definition, it is easy to verify that $D(P\|P_1 \otimes P_2) = H(x) - H(x|y)$. Observe that $D(P\|P_1 \otimes P_2) = 0$ if, and only if, x and y are independent. It can be shown (Cover and Thomas (1991), p.300) that

¹⁸In fact, one can take $\theta(\delta) = -\delta \log_2 \frac{\delta}{|A_1|}$ for $\delta \leq \frac{1}{2}$. See Cover and Thomas (1991), p. 488.

$D(\mathbb{P} \parallel \mathbb{Q}) \geq \frac{1}{2 \ln 2} \|\mathbb{P} - \mathbb{Q}\|_1^2$, and hence $H(x) - H(x|y) \geq \frac{1}{2 \ln 2} \|\mathbb{P} - \mathbb{P}_1 \otimes \mathbb{P}_2\|_1^2$. It follows from (19) that

$$(20) \quad \|\mathbb{P} - \mathbb{P}_1 \otimes \mathbb{P}_2\|_1 = \sum_{a,b} |\mathbb{P}(a,b) - \mathbb{P}_1(a)\mathbb{P}_2(b)| \leq \sqrt{2 \ln 2 (\theta(\delta) + \delta)}.$$

Thus, setting $\xi(\delta) = \sqrt{2(\theta(\delta) + \delta) \ln 2}$, we have

$$\begin{aligned} \mathbf{E}[g(x,y)] &= \sum_{a,b} \mathbb{P}(a,b)g(a,b) \\ &\geq \sum_{a,b} \mathbb{P}_1(a)\mathbb{P}_2(b)g(a,b) - \|g\|\xi(\delta) && \text{by (20)} \\ &\geq \sum_{a,b} \alpha(a)\mathbb{P}_2(b)g(a,b) - \|g\|\delta - \|g\|\xi(\delta) && \text{by (ii)} \\ &\geq \min_b g(\alpha,b) - \|g\|(\delta + \xi(\delta)). \end{aligned}$$

This completes the proof.

Q.E.D.

APPENDIX II

We present an alternative proof of Theorem 3 that does not make use of Lemma 3. The construction of the strategy set Ψ_1 is similar to that presented in the main text and we will avoid duplicating detailed descriptions of the notations used.

CONSTRUCTION OF Ψ_1 : The set F_n is now defined by means of two sequences of nonnegative reals, $(\gamma_n)_n$ with $\gamma_n \leq \bar{\gamma}$ and $(\eta_n)_n$ where $\eta_n \geq \frac{|A_1|}{d_n}$ and $\eta_n \xrightarrow{n \rightarrow \infty} 0$. As before, if $\gamma_n = 0$, then we set F_n to be a singleton. For n with $\gamma_n > 0$, we let

$$(21) \quad F_n = \left\{ (a_1, \dots, a_{d_n}) \in A_1^{d_n} : \sum_{a \in A_1} \left| \frac{1}{d_n} \sum_{k=1}^{d_n} \mathbf{1}(a_k = a) - \alpha_n(a) \right| \leq \eta_n \right\}.$$

The condition $\eta_n \geq \frac{|A_1|}{d_n}$ ensures that $F_n \neq \emptyset$ in this case.

The sequence $(\eta_n)_n$ is chosen to satisfy, in addition, the following property. Let $\mathbf{x} = (x_1, x_2, \dots)$ be a sequence of independent A_1 -valued random variables where x_t is distributed according to α_n whenever t is in the n -th block, i.e. $t_{n-1} + 1 \leq t \leq t_n$. Then we require¹⁹

$$(22) \quad \sum_{n=1}^{\infty} \mathbb{P}(\mathbf{x}[n] = (x_{t_{n-1}+1}, \dots, x_{t_n}) \notin F_n) < \infty.$$

As before, we define $F = \{\mathbf{a} = (a_1, a_2, \dots) \in A_1^\infty : \mathbf{a}[n] = (a_{t_{n-1}+1}, \dots, a_{t_n}) \in F_n\}$ and then $\Psi_1 = \{\sigma\langle \mathbf{a} \rangle : \mathbf{a} \in F\}$.

¹⁹For n with $\gamma_n = 0$, it is obvious that $\mathbb{P}(\mathbf{x}[n] \notin F_n) = 0$. For n with $\gamma_n > 0$, note that $\mathbf{x}[n] \notin F_n$ implies that $\left| \frac{1}{d_n} \sum_{k=1}^{d_n} \mathbf{1}(x_{t_{n-1}+k} = a) - \alpha_n(a) \right| > \frac{\eta_n}{|A_1|}$ for some $a \in A_1$. For each $a \in A_1$ and $k = 1, \dots, d_n$, the random variable $\mathbf{1}(x_{t_{n-1}+k} = a)$ takes values 0 and 1, and has mean $\alpha_n(a)$. Hence by a large deviation inequality due to Hoeffding (1963) we have

$$\mathbb{P}\left(\left|\frac{1}{d_n} \sum_{k=1}^{d_n} \mathbf{1}(x_{t_{n-1}+k} = a) - \alpha_n(a)\right| > \frac{\eta_n}{|A_1|}\right) \leq 2 \exp\left(-2d_n \frac{\eta_n^2}{|A_1|^2}\right),$$

and so

$$\mathbb{P}(\mathbf{x}[n] \notin F_n) \leq 2|A_1| \exp\left(-2d_n \frac{\eta_n^2}{|A_1|^2}\right).$$

Take, for example, $\eta_n = |A_1|/d_n^{1/4}$ ($> |A_1|/d_n$). Then the exponential term on the right side of the above inequality is $\exp(-2\sqrt{d_n})$ and (22) holds.

CONSTRUCTION OF $\hat{\sigma} \in \Delta(\Psi_1)$: Define a sequence of A_1 -valued random variables $\hat{\mathbf{x}} = (\hat{x}_1, \hat{x}_2, \dots)$ by

$$\hat{\mathbf{x}}[n] = (\hat{x}_{t_{n-1}+1}, \dots, \hat{x}_{t_n}) = \begin{cases} \mathbf{x}[n] & \text{if } \mathbf{x}[n] \in F_n, \\ \bar{\mathbf{a}}[n] & \text{otherwise.} \end{cases}$$

Let $\hat{\sigma} = \sigma(\hat{\mathbf{x}})$. Note that $\hat{\sigma}$ is indeed a mixture of strategies in Ψ_1 .

VERIFICATION OF THE THEOREM: As before, in order to verify that Ψ_1 has the property (i) of the theorem, it is enough to ensure (7). By estimating $|F_n|$ in a manner analogous to the proof in the main text, one sees that it suffices to ensure (8).

To derive a sufficient condition to be verified in order to show that $\hat{\sigma}$ has the property (ii), observe that the L_1 -distance between the conditional distributions of $\mathbf{x}[n]$ and $\hat{\mathbf{x}}[n]$ given $\mathbf{x}[1], \dots, \mathbf{x}[n-1]$ is at most $2\mathbb{P}(\mathbf{x}[n] \notin F_n)$, that is,

$$\sum_{\mathbf{a}_n \in A_1^{t_n}} \left| \mathbb{P}(\mathbf{x}[n] = \mathbf{a}_n) - \mathbb{P}(\hat{\mathbf{x}}[n] = \mathbf{a}_n) \right| \leq 2\mathbb{P}(\mathbf{x}[n] \notin F_n).$$

It follows that, in the n -th block, we have

$$\min_{\tau \in \Sigma_2} \mathbf{E}_{\hat{\sigma}, \tau} \left[\sum_{t=t_{n-1}+1}^{t_n} g(a_t, b_t) \right] \geq d_n U(\gamma_n) - 2\|g\| \mathbb{P}(\mathbf{x}[n] \notin F_n)$$

and hence, for each $N = 1, 2, \dots$,

$$\min_{\tau \in \Sigma_2} \mathbf{E}_{\hat{\sigma}, \tau} \left[\sum_{t=1}^{t_N} g(a_t, b_t) \right] \geq \sum_{n=1}^N d_n U(\gamma_n) - 2\|g\| \sum_{n=1}^N \mathbb{P}(\mathbf{x}[n] \notin F_n).$$

Thus, by virtue of (22), in order to show part (ii) of the theorem it suffices to choose $(\gamma_n)_n$ so that (10) holds.

The part of the proof that exhibits a choice of $(\gamma_n)_n$ that satisfy (8) and (10) as well as the verification of (iii) is identical to the one in the main text and thus is omitted.

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