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Entropy Games*

Eugene Asarin¹, Julien Cervelle², Aldric Degorre¹, Cătălin Dima², Florian Horn¹,
and Victor Kozyakin³

¹LIAFA, University Paris Diderot and CNRS, France

²LACL, University Paris-Est Créteil, France

³IITP, Russian Academy of Science, Russia

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Abstract

An entropy game is played on a finite arena by two-and-a-half players: Despot, Tribune and non-deterministic People. Whenever Despot and Tribune decide of their actions, it remains a set L of possible behaviors of People. Despot aims the entropy (growth rate) of L to be as small as possible, while Tribune wants to make it as large as possible. The main result is that the entropy game is determined, and that the optimal strategies for Despot and Tribune are positional. The analysis is based on that of matrix multiplication games, also novel and generalizing the theory of joint spectral radius.

Keywords: Game theory, entropy, joint spectral radius.

1 Introduction

In last years, some of us have been working on a new non-probabilistic quantitative approach to classical models in computer science based on the notion of language entropy (growth rate). This approach gave new insights about timed automata and languages [1] as well as temporal logics [2]. In this article, we apply it to game theory and obtain a new natural class of games which we call *entropy games*.

Entropy games (EGs) are played on a finite arena by two-and-a-half players: *Despot*, *Tribune* and the non-deterministic *People*. The game is played in a turn-based way, in infinite time. Whenever Despot and Tribune decide of their actions (strategies σ and τ), it remains a set $L(\sigma, \tau)$ (an ω -language) of possible behaviors of People. Despot aims $L(\sigma, \tau)$ to be as small as possible, while Tribune wants to make this language as large as possible. Formally the payoff of the game is the entropy of $L(\sigma, \tau)$, with Despot minimizing and Tribune maximizing this value. The main result of the article is that EGs are determined, and that the optimal strategies for Despot and Tribune are positional.

The analysis of EGs is based on *matrix multiplication games* (MMGs), which are, in our opinion, novel and interesting on their own. In such a game, two players, Adam and Eve, each possess a set of matrices, respectively \mathcal{A} and \mathcal{E} . The game is also played in a turn-based way, on infinite time. At every turn, the player writes a matrix of his or her set. Adam wants the norm of the product of matrices $A_1 E_1 A_2 E_2 \dots$ obtained to be as small as possible, while Eve wants it to be as large as possible. Formally, the payoff is the growth rate of the norm of the product.

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The mathematical interest of MMGs comes from the remark that, in the case when one of the two players is trivial (i.e. his or her set contains only the identity matrix), the game turns into the classical, and difficult, problems of joint spectral radius and joint spectral subradius of a set of matrices [19]. We believe that the general case is even more difficult to analyze. Fortunately, for a particular class of MMGs – corresponding exactly to EGs – when the sets \mathcal{A} and \mathcal{E} are so-called *independent row uncertainty sets* of non-negative matrices [4], the game can be solved: it is determined, and for each player the optimal strategy is to write one and the same matrix at every turn. This result is based on a new *minimax* theorem on the spectral radius of products of the type AB where both A and B belong to sets of matrices with independent row uncertainties.

We also analyse the complexity of the games considered and prove that comparing their value to a rational constant can be done with complexity $\text{NP} \cap \text{coNP}$.

The article is structured as follows. In Section 2 we recall useful notions from linear algebra and language theory. In Section 3 we formally define the two games and establish a link between them. In Section 4 we prove the key technical minimax theorem for matrices. In Section 5 we prove the main properties of the two games. In Section 6 we provide an illustrating example and relate the EGs studied here to classical mean-payoff games and novel population games. We conclude by a discussion on the results and perspectives.

2 Preliminaries

2.1 Some linear algebra

Given two vectors $x, y \in \mathbb{R}^N$, we write $x \geq y$ (resp. $x > y$), if $x_i \geq y_i$ for each $1 \leq i \leq N$. Similar notations will be applied to matrices. We denote by $\|\cdot\|$ the 1-norm of vectors and matrices. Note that, for non-negative vectors and matrices, $\|x\| = \sum_i x_i$.

Let A be an $(N \times N)$ -matrix. Its *spectral radius* is defined as the maximal modulus of its eigenvalues and denoted by $\rho(A)$. It characterizes the growth rate of A^n for $n \rightarrow \infty$: according to Gelfand's formula $\rho(A) = \lim_{n \rightarrow \infty} \|A^n\|^{1/n}$. The spectral radius depends continuously on the matrix, and is monotone for non-negative matrices [11, Corollary 8.1.19]:

$$0 \leq A \leq B \Rightarrow \rho(A) \leq \rho(B). \quad (1)$$

If X and Y are matrices of dimensions $M \times N$ and $N \times M$ respectively, then

$$\rho(XY) = \rho(YX). \quad (2)$$

This equality follows from the fact that the non-zero eigenvalues of the matrices XY and YX coincide: indeed, if $XYu = \lambda u$ for a number $\lambda \neq 0$ and a vector $u \neq 0$, then $v = Yu \neq 0$, and therefore $YXv = YXYu = \lambda Yu = \lambda v$.

If $A > 0$, i.e. all the elements of A are positive, then by the Perron-Frobenius theorem, the number $\rho(A)$ is a simple eigenvalue of the matrix A , and all the other eigenvalues of A are strictly less than $\rho(A)$ by modulus. The eigenvector $v = (v_1, v_2, \dots, v_N)^T$ corresponding to the eigenvalue $\rho(A)$ (normalized, for example, by the equation $\sum v_i = 1$) is uniquely determined and positive.

Following [4], given N sets of M -rows \mathcal{A}_i we define the *IRU-set* (independent row uncertainty set) \mathcal{A} of $(N \times M)$ -matrices that consists of all matrices of the form

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1M} \\ a_{21} & a_{22} & \cdots & a_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} & a_{N2} & \cdots & a_{NM} \end{bmatrix},$$

wherein each of the rows $a_i = [a_{i1}, a_{i2}, \dots, a_{iM}]$ belongs to the respective \mathcal{A}_i .

We will need several simple properties of IRU-sets (proved in Appendix).

Lemma 1. *For an IRU-set \mathcal{A} formed by sets of rows $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_N$ the following holds:*

- (i) for any matrix B the set $\mathcal{A}B = \{AB \mid A \in \mathcal{A}\}$ is IRU as well;
- (ii) the convex hull $\text{conv}(\mathcal{A})$ is the IRU-set formed by the row sets $\text{conv}(\mathcal{A}_1), \dots, \text{conv}(\mathcal{A}_N)$;
- (iii) the set \mathcal{A} is compact if and only if so are all the row sets $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_N$.

2.2 Joint spectral radius and subradius

The *joint spectral radius* [7, 8, 16] of a bounded set \mathcal{A} of $(N \times N)$ -matrices characterizes the maximal growth rate of products of n matrices from the set and admits the following equivalent definitions (where the identity between the upper and the lower formulas constitutes the famous Berger-Wang's Theorem [3]):

$$\begin{aligned} \hat{\rho}(\mathcal{A}) &= \lim_{n \rightarrow \infty} \sup \left\{ \|A_n \cdots A_1\|^{1/n} \mid A_i \in \mathcal{A} \right\} = \inf_{n \geq 1} \sup \left\{ \|A_n \cdots A_1\|^{1/n} \mid A_i \in \mathcal{A} \right\} \\ &= \lim_{n \rightarrow \infty} \sup \left\{ \rho(A_n \cdots A_1)^{1/n} \mid A_i \in \mathcal{A} \right\} = \sup_{n \geq 1} \sup \left\{ \rho(A_n \cdots A_1)^{1/n} \mid A_i \in \mathcal{A} \right\}. \end{aligned} \quad (3)$$

For a compact (closed and bounded) set \mathcal{A} , the suprema in (3) may be replaced by maxima.

The *joint spectral subradius* [10], or *lower spectral radius*, corresponds to the minimal growth rate of products of matrices:

$$\begin{aligned} \check{\rho}(\mathcal{A}) &= \lim_{n \rightarrow \infty} \inf \left\{ \|A_n \cdots A_1\|^{1/n} \mid A_i \in \mathcal{A} \right\} = \inf_{n \geq 1} \inf \left\{ \|A_n \cdots A_1\|^{1/n} \mid A_i \in \mathcal{A} \right\} \\ &= \lim_{n \rightarrow \infty} \inf \left\{ \rho(A_n \cdots A_1)^{1/n} \mid A_i \in \mathcal{A} \right\} = \inf_{n \geq 1} \inf \left\{ \rho(A_n \cdots A_1)^{1/n} \mid A_i \in \mathcal{A} \right\}. \end{aligned} \quad (4)$$

The equivalence of the characterizations is established in [10, Theorem B1] for finite sets \mathcal{A} , and in [18, Lemma 1.12] and [6, Theorem 1] for arbitrary sets \mathcal{A} .

Calculating the joint and lower spectral radii is a challenging problem, and only in exceptional cases these characteristics may be found explicitly, see, e.g., [12, 13] and the bibliography therein. The case of compact IRU-sets of non-negative matrices is such an exception, for which $\hat{\rho}$ and $\check{\rho}$ admit a simple characterization: as stated in [14, Theorem 2], for such a set \mathcal{A} the following equalities hold:

$$\hat{\rho}(\mathcal{A}) = \max_{A \in \mathcal{A}} \rho(A), \quad \check{\rho}(\mathcal{A}) = \min_{A \in \mathcal{A}} \rho(A). \quad (5)$$

Compact IRU-sets of non-negative matrices and their convex hulls have another useful property: as is shown in [14, Corollary 1],

$$\max_{A \in \mathcal{A}} \rho(A) = \max_{A \in \text{conv}(\mathcal{A})} \rho(A), \quad \min_{A \in \mathcal{A}} \rho(A) = \min_{A \in \text{conv}(\mathcal{A})} \rho(A), \quad (6)$$

and hence

$$\hat{\rho}(\mathcal{A}) = \hat{\rho}(\text{conv}(\mathcal{A})), \quad \check{\rho}(\mathcal{A}) = \check{\rho}(\text{conv}(\mathcal{A})). \quad (7)$$

2.3 Entropy of an ω -language

The notion of entropy of a language and methods for its computing in the case of regular languages were introduced in [5] for finite words and in [17] for infinite ones. We will use the latter definition. The entropy of an ω -language $L \subseteq \Sigma^\omega$ is defined as

$$H(L) = \limsup_{n \rightarrow \infty} \frac{\log |\text{pref}_n(L)|}{n}$$

(all the logarithms in this article are in base 2), where $\text{pref}_n(L)$ is the set of prefixes of length n of infinite words in L . Intuitively, $H(L)$ is the information content (“bandwidth”), measured in bits per symbol, in typical words of the language. In particular, $H(\Sigma^\omega) = \log |\Sigma|$.

For a regular $L \subseteq \Sigma^\omega$ accepted by a given Büchi automaton, its entropy can be effectively computed as follows: compute the (finite) automaton recognizing $\text{pref}(L)$, determinize it, and compute the entropy as the logarithm of the spectral radius of the adjacency matrix of the automaton obtained.

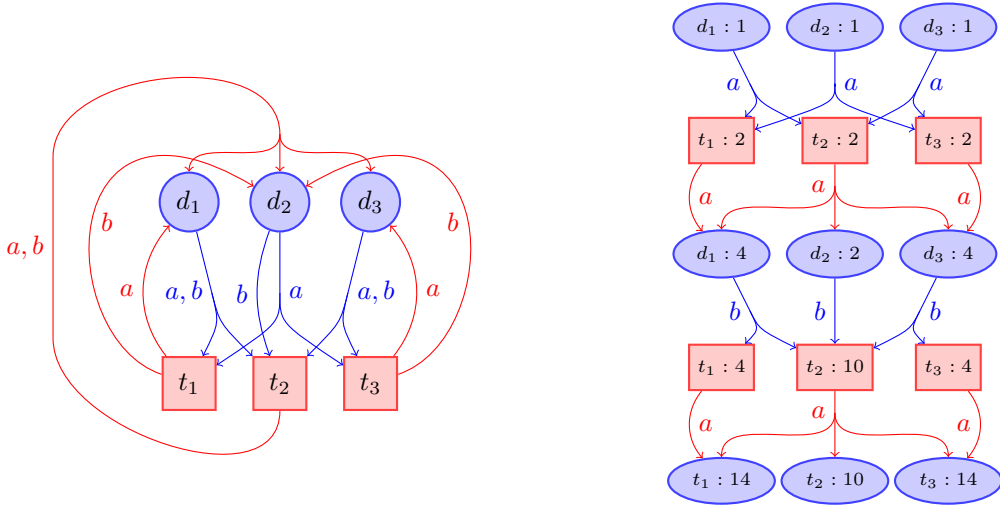


Figure 1: *Left.* Arena of our running example of entropy game. Circles are states of the Despot while squares are states of the Tribune. At each move, the player has to choose between action a or b , the outcome of which may sometimes be non-deterministic (e.g. when Despot plays b in state d_2 , the next state may non-deterministically be either t_1 or t_3).

Right. A finite play on this arena. Despot plays ab while Tribune plays aa . We only give, for each step, the amount of words that end up in each state controlled by the active player.

3 Entropy games and matrix multiplication games

3.1 Entropy games

Consider the arena (D, T, Σ, Δ) where D and T are disjoint finite sets of vertices (of two players), Σ a finite alphabet of actions and $\Delta \subseteq T \times \Sigma \times D \cup D \times \Sigma \times T$ is a transition relation. Given such an arena, we define a game with two-and-a-half players: Despot, Tribune and People that plays non-deterministically. People chooses the initial state in D . When the game is in a state d of D , Despot plays an action $a \in \Sigma$ and the game changes to some $t \in T$ (chosen by People) such that $(d, a, t) \in \Delta$. Then, Tribune plays an action $b \in \Sigma$ and the game changes its state to $d' \in D$, again chosen by People and such that $(t, b, d') \in \Delta$. It is again Despot's turn. The players must not block the game: they always choose an action that has a corresponding transition $(d, a, \cdot) \in \Delta$, resp. $(t, b, \cdot) \in \Delta$. We suppose the arena non-blocking: at every state there is at least one such transition. Figure 1 shows an example of such an arena, which we will use as a running example in this paper.

A *play* of the EG is a finite or infinite sequence $\pi \in (D \cdot \Sigma \cdot T \cdot \Sigma)^\infty$ compatible with the transition relation Δ . Note that four letters in a row correspond to one turn of the game. A *strategy* σ for Despot is a function $(D \cdot \Sigma \cdot T \cdot \Sigma)^* \cdot D \rightarrow \Sigma$ which, given any finite play ending in a D state, outputs an action taken by Despot. The strategy is positional if it only depends on the current state of the game, i.e. it can be expressed just as $\sigma(d)$. A *strategy* τ for Tribune is a function $(D \cdot \Sigma \cdot T \cdot \Sigma)^* \cdot D \cdot \Sigma \cdot T \rightarrow \Sigma$ which, given any finite play ending in a T state, outputs the action taken by Tribune. The strategy is positional if it only depends on the current state of the game.

In a natural way we define plays compatible with a Despot's strategy σ , or with a Tribune's strategy τ . Then, given σ and τ , we have an ω -language $L(\sigma, \tau)$ containing all the plays compatible with σ and τ . In other words, $L(\sigma, \tau)$ is the set of runs that People can choose whenever Despot and Tribune commit themselves to σ and τ .

What makes EGs different from other games (parity/mean-payoff etc.) is that the payoff depends not on the run of the game, but on the whole set of possible runs. More precisely, the

payoff (the amount that Despot pays to Tribune) is defined as

$$P(\sigma, \tau) = \limsup_{n \rightarrow \infty} |\text{pref}_{4n}(L(\sigma, \tau))|^{1/n},$$

that is the growth rate (w.r.t. the number of turns) of the number of plays available to the People under the D-strategy σ and the T-strategy τ . Note that the payoff is a monotone function of the entropy of $L(\sigma, \tau)$, indeed $P(\sigma, \tau) = 2^{4H(L(\sigma, \tau))}$, i.e. Despot tries to diminish the entropy while Tribune aims to augment it.

3.2 Matrix multiplication games

Let \mathcal{A} be a set of $M \times N$ -matrices and \mathcal{E} of $N \times M$ -matrices. The MMG between two players, Adam and Eve, is played as follows: in turn, for every $i \in \mathbb{N}$, Adam writes a matrix $A_i \in \mathcal{A}$ and then Eve writes a matrix $E_i \in \mathcal{E}$.

Formally, we define a *play* as an infinite sequence $A_1 E_1 A_2 E_2 \dots A_i E_i \dots$ with $A_i \in \mathcal{A}$ and $E_i \in \mathcal{E}$. A strategy for Adam is a function $\sigma : (\mathcal{A} \cdot \mathcal{E})^* \rightarrow \mathcal{A}$ which maps any finite history (which is a sequence of matrices) into the current move of Adam. Similarly, a strategy for Eve is a mapping $\tau : (\mathcal{A} \cdot \mathcal{E})^* \cdot \mathcal{A} \rightarrow \mathcal{E}$. A strategy is called *constant* if it does not depend on the history, i.e. is given by just one matrix: $\sigma = A \in \mathcal{A}$ or $\tau = E \in \mathcal{E}$.

We define a play compatible with a strategy σ (or τ) in a natural way. Note that, given a strategy σ for Adam and a strategy τ for Eve, there exists a unique play $\pi(\sigma, \tau)$ compatible with both of them. The payoff of a play $\pi = A_1 E_1 A_2 E_2 \dots A_i E_i \dots$ (that is the amount that Adam pays to Eve) is the growth rate of the norm of the infinite product of matrices:

$$P(\pi) = P(\sigma, \tau) = \limsup_{k \rightarrow \infty} \left\| \prod_{i=1}^k A_i E_i \right\|^{1/k}.$$

3.3 Relations between the two kinds of games

Let $\mathbf{A} = (D, T, \Sigma, \Delta)$ be an arena with $D = \{d_1, \dots, d_M\}$ and $T = \{t_1, \dots, t_N\}$. We define matrix sets \mathcal{A}, \mathcal{E} as follows. For each Despot's vertex $d_i \in D$, and action $a \in \Sigma$ we define the row $c_{ia} = [c_{ia,1}, \dots, c_{ia,N}]$ where $c_{ia,j} = 1$ if $(d_i, a, t_j) \in \Delta$ and $c_{ia,j} = 0$ otherwise. Next we define the row set $\mathcal{A}_i = \{c_{ia} \neq 0 \mid a \in \Sigma\}$ (non-zero rows correspond to non-blocking actions). Row sets $\mathcal{A}_1, \dots, \mathcal{A}_M$ determine an IRU-set of matrices \mathcal{A} . The IRU-set \mathcal{E} corresponding to Tribune's actions is defined similarly. In the running example Figure 1, for instance, the row sets are the following: $\mathcal{A}_1 = \{[1, 1, 0]\}$, $\mathcal{A}_2 = \{[0, 1, 0], [1, 0, 1]\}$, $\mathcal{A}_3 = \{[0, 1, 1]\}$, $\mathcal{B}_1 = \{[0, 1, 0], [1, 0, 0]\}$, $\mathcal{B}_2 = \{[1, 1, 1]\}$, $\mathcal{B}_3 = \{[0, 1, 0], [0, 0, 1]\}$.

There is a natural bijection between the positional strategies of Despot and the set \mathcal{A} : to any positional strategy $\sigma : D \rightarrow \Sigma$ we associate the matrix $A_\sigma \in \mathcal{A}$ with i -th row $c_{i, \sigma(d_i)}$ for Adam. Similarly, to a positional strategy of Tribune τ we associate Eve's matrix $E_\tau \in \mathcal{E}$.

Lemma 2. *Let \mathbf{A} be an arena and \mathcal{A}, \mathcal{E} the corresponding IRU matrix sets. Then for every couple of strategies (σ, τ) of Despot and Tribune in the EG on \mathbf{A} there exists a couple of strategies (ς, θ) of Adam and Eve in the MMG $(\text{conv}(\mathcal{A}), \text{conv}(\mathcal{E}))$ with exactly the same payoff. Moreover, if σ is positional, then ς is constant and permanently chooses A_σ . The case of positional τ is similar.*

Proof. Assume $D = \{d_1, \dots, d_M\}$ and $T = \{t_1, \dots, t_N\}$. Given arbitrary strategies (σ, τ) for the two players in the EG, let us represent the set of all compatible plays as a forest. Its nodes are labeled by elements of D on even levels and elements of T on odd levels, and its edges are labeled by symbols in Σ . The label of a node q is denoted $\ell(q)$; the sequence of labels on the path reaching q from the appropriate root in the forest is referred to as its address $\alpha(q)$. The forest \mathbf{F} is defined inductively as follows:

- \mathbf{F} has M root nodes labeled by d_1, \dots, d_M ;

- all the outgoing edges of a node q labeled $d \in D$ carry the symbol $a = \sigma(\alpha(q))$ and the sons of the node q correspond to (and are labeled by) the elements of $\{t \mid (d, a, t) \in \Delta\}$;
- all the outgoing edges of a node q labeled $t \in T$ carry the symbol $b = \tau(\alpha(q))$ and the sons of the node q correspond to (and are labeled by) the elements of $\{d \mid (t, a, d) \in \Delta\}$.

The payoff of the EG can be characterized in terms of the growth rate of this forest:

$$P(\sigma, \tau) = \limsup_{n \rightarrow \infty} |\mathbf{F}_{2n}|^{1/n},$$

where \mathbf{F}_k denotes the set of nodes of \mathbf{F} at the level k . Indeed $L(\sigma, \tau)$ is the set of labels of infinite paths of \mathbf{F} , hence $\text{pref}(L(\sigma, \tau))$ is the set of addresses of nodes in \mathbf{F} (we use the fact that our strategies are required to be non-blocking). To words of length $4n$ in $\text{pref}(L(\sigma, \tau))$ correspond addresses of nodes of level $2n$, and thus

$$\limsup_{n \rightarrow \infty} |\text{pref}_{4n}(L(\sigma, \tau))|^{1/n} = \limsup_{n \rightarrow \infty} |\mathbf{F}_{2n}|^{1/n}$$

as required.

Let us characterize the number of nodes $|\mathbf{F}_{2n}|$ in terms of matrices. Let the vector $x^{(n)} = (x_1^{(n)}, \dots, x_j^{(n)})$ be such that $x_i^{(n)}$ is the number of nodes labeled by d_i on $2n$ -th level of \mathbf{F} ; similarly let $y^{(n)} = (y_1^{(n)}, \dots, y_N^{(n)})$ be such that $y_j^{(n)}$ is the number of nodes labeled by t_j on $(2n+1)$ -th level of \mathbf{F} . To relate $y^{(n)}$ to $x^{(n)}$ we observe that

$$y_j^{(n)} = \sum_{i=1}^M \sum_{a \in \Sigma} |\{q \in \mathbf{F}_{2n} \mid \ell(q) = d_i \wedge \sigma(\alpha(q)) = a\}| c_{ia,j}.$$

Indeed, every node on level $2n$ with label d_i and action a generates on the next level a node with label t_j whenever $c_{ia,j} = 1$. Summing up on all i, a and q we obtain the quantity $y_j^{(n)}$. The expression for y can be rewritten as

$$y_j^{(n)} = \sum_{i=1}^M x_i^{(n)} \sum_{a \in \Sigma} \mu_{ia} c_{ia,j} \quad (8)$$

with $\mu_{ia}^{(n)} = |\{q \in \mathbf{F}_{2n} \mid \ell(q) = d_i \wedge \sigma(\alpha(q)) = a\}| / x_i^{(n)}$ (whenever $x_i^{(n)} = 0$, coefficients $\mu_{ia}^{(n)}$ can be chosen arbitrarily, only respecting conditions (9) below). Intuitively, $\mu_{ia}^{(n)}$ is the proportion among the states d_i on level $2n$, of those for which Despot takes the action a . In matrix form (8) can be rewritten as $y^{(n)} = x^{(n)} A_n$ with $A_{n,ij} = \sum_{a \in \Sigma} \mu_{ia}^{(n)} c_{ia,j}$. We notice that

$$\mu_{ia}^{(n)} \geq 0 \text{ and } \sum_{a \in \Sigma} \mu_{ia}^{(n)} = 1, \quad (9)$$

thus i -th row of A_n belongs to $\text{conv}(\mathcal{A}_i)$, hence $A_n \in \text{conv}(\mathcal{A})$. Similarly, $x^{(n+1)} = y^{(n)} E_n$ for some $E_n \in \text{conv}(\mathcal{E})$. Initially $x^{(0)} = (1, \dots, 1)$, and clearly $|\mathbf{F}_n| = x^{(n)} \cdot (1, \dots, 1)^\top$, hence

$$|\mathbf{F}_{2n}| = (1, \dots, 1) A_0 E_0 A_1 E_1 \cdots A_{n-1} E_{n-1} (1, \dots, 1)^\top = \|A_0 E_0 A_1 E_1 \cdots A_{n-1} E_{n-1}\|.$$

Taking in the MMG over $(\text{conv}(\mathcal{A}), \text{conv}(\mathcal{E}))$ the strategies ς and θ , which choose matrices $A_0, E_0, A_1, E_1, \dots$ we obtain the required:

$$P_{\text{EG}}(\sigma, \tau) = \limsup_{n \rightarrow \infty} |\mathbf{F}_{2n}|^{1/n} = \limsup_{n \rightarrow \infty} \|A_0 E_0 A_1 E_1 \cdots A_{n-1} E_{n-1}\|^{1/n} = P_{\text{MMG}}(\varsigma, \theta).$$

It is easy to see that for positional σ our construction gives $A_n = A_\sigma$ for all n . \square

Note that Lemma 2 provides a rather weak relation between two games and does not mean, by itself, that the two games have the same value. However, we will show later (cf. Lemma 6) that optimal **constant** strategies in the MMG that belong to \mathcal{A} and \mathcal{E} correspond to optimal positional strategies are the EG.

4 Minimax theorem for IRU-sets of matrices

4.1 Auxiliary lemmas

The former lemma on spectral radius bounds for non-negative matrices is quite standard in Perron-Frobenius theory, for completeness we provide a proof in the Appendix. The latter concerns IRU-sets of matrices and is novel.

Lemma 3. *Let A be a non-negative $(N \times N)$ -matrix; then the following properties hold:*

- (i) *if $Au \leq \rho u$ for some vector $u > 0$, then $\rho \geq 0$ and $\rho(A) \leq \rho$;*
- (ii) *if furthermore $A > 0$ and $Au \neq \rho u$, then $\rho(A) < \rho$;*
- (iii) *if $Au \geq \rho u$ for some non-zero vector $u \geq 0$ and some number $\rho \geq 0$, then $\rho(A) \geq \rho$;*
- (iv) *if furthermore $Au \neq \rho u$, then $\rho(A) > \rho$.*

Lemma 4 (hourglass principle¹). *Let \mathcal{A} be an IRU-set of $(N \times M)$ -matrices and let $\tilde{A}u = v$ for some matrix $\tilde{A} \in \mathcal{A}$ and vectors u, v . Then the following holds:*

- (i) *either $Au \geq v$ for all $A \in \mathcal{A}$ or exists a matrix $\bar{A} \in \mathcal{A}$ such that $\bar{A}u \leq v$ and $\bar{A}u \neq v$;*
- (ii) *either $Au \leq v$ for all $A \in \mathcal{A}$ or exists a matrix $\bar{A} \in \mathcal{A}$ such that $\bar{A}u \geq v$ and $\bar{A}u \neq v$.*

Clearly the hourglass principle does not hold for general sets of matrices.

Proof. To prove (i), we represent the vectors u and v in coordinate form:

$$u = (u_1, u_2, \dots, u_M)^\top, \quad v = (v_1, v_2, \dots, v_N)^\top.$$

Suppose that for some matrix $A = (a_{ij}) \in \mathcal{A}$ the inequality $Au \geq v$ fails. Then

$$a_{i1}u_1 + a_{i2}u_2 + \dots + a_{iM}u_M < v_i$$

for some $i \in \{1, 2, \dots, N\}$; we may assume $i = 1$ without loss of generality. In this case, the matrix

$$\bar{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1M} \\ \tilde{a}_{21} & \tilde{a}_{22} & \dots & \tilde{a}_{2M} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{N1} & \tilde{a}_{N2} & \dots & \tilde{a}_{NM} \end{bmatrix},$$

obtained from the matrix $\tilde{A} = (\tilde{a}_{ij})$ replacing the first row by $a_1 = [a_{11}, a_{12}, \dots, a_{1M}]$, yields the inequalities

$$a_{11}u_1 + a_{12}u_2 + \dots + a_{1M}u_M < v_1$$

and

$$\tilde{a}_{i1}u_1 + \tilde{a}_{i2}u_2 + \dots + \tilde{a}_{iM}u_M = v_i, \quad i = 2, 3, \dots, N.$$

Consequently, $\bar{A}u \leq v$ and $\bar{A}u \neq v$, which completes the proof of the first statement of the lemma. The proof of statement (ii) is similar. \square

¹Imagine that the sets $B_l = \{x : x \leq v\}$ and $B_u = \{x : v \leq x\}$ form the lower and upper bulbs of an hourglass with the neck at the point v . Then Lemma 4 asserts that either all the grains Au fill one of the bulbs, or it remains at least one grain in the other bulb.

4.2 Minimax theorem

The study of minimax relations will be based on the following well-known fact:

Lemma 5 (see [20, Section 13.4]). *Let $f(x, y)$ be a continuous function on the product of compact spaces $X \times Y$. Then*

$$\min_x \max_y f(x, y) \geq \max_y \min_x f(x, y).$$

The exact equality holds if and only if there exists a saddle point, i.e. a point (x_0, y_0) satisfying the inequalities

$$f(x_0, y) \leq f(x_0, y_0) \leq f(x, y_0)$$

for all $x \in X, y \in Y$.

We are ready to state the key theorem of this article.

Theorem 1. *Let \mathcal{A} be a compact IRU-set of non-negative $(N \times M)$ -matrices and \mathcal{B} be a compact IRU-set of non-negative $(M \times N)$ -matrices. Then*

$$\min_{A \in \mathcal{A}} \max_{B \in \mathcal{B}} \rho(AB) = \max_{B \in \mathcal{B}} \min_{A \in \mathcal{A}} \rho(AB). \quad (10)$$

In the rest of the article we will denote this minimax by $\text{mm}(\mathcal{A}, \mathcal{B})$.

Proof. According to Lemma 5, minimax equality (10) may occur if and only if some matrices $\tilde{A} \in \mathcal{A}$ and $\tilde{B} \in \mathcal{B}$ satisfy the inequalities

$$\rho(\tilde{A}B) \leq \rho(\tilde{A}\tilde{B}) \quad \text{for all } B \in \mathcal{B}; \quad (11)$$

$$\rho(\tilde{A}\tilde{B}) \leq \rho(A\tilde{B}) \quad \text{for all } A \in \mathcal{A}. \quad (12)$$

Consider first the case when all the matrices in \mathcal{A} and \mathcal{B} are **positive**. To construct the matrices $\tilde{A} \in \mathcal{A}$ and $\tilde{B} \in \mathcal{B}$ proceed as follows. For each $B \in \mathcal{B}$ let $A_B \in \mathcal{A}$ be a matrix which minimizes (in A) the quantity $\rho(AB)$. Such a matrix A_B exists due to compactness of the set \mathcal{A} and continuity of the function $\rho(AB)$ in A and B . Then, for each matrix $B \in \mathcal{B}$, the relations $\rho(A_B B) = \min_{A \in \mathcal{A}} \rho(AB) \leq \rho(\tilde{A}B)$ hold for all $A \in \mathcal{A}$. Let \tilde{B} be the matrix maximizing $\min_{A \in \mathcal{A}} \rho(AB)$ over the set \mathcal{B} , and let $\tilde{A} = A_{\tilde{B}}$. In this case

$$\max_{B \in \mathcal{B}} \rho(A_B B) = \max_{B \in \mathcal{B}} \min_{A \in \mathcal{A}} \rho(AB) = \min_{A \in \mathcal{A}} \rho(A\tilde{B}) = \rho(A_{\tilde{B}}\tilde{B}) = \rho(\tilde{A}\tilde{B}), \quad (13)$$

which implies inequality (12) for all $A \in \mathcal{A}$, and it remains to prove (11) for all $B \in \mathcal{B}$.

Let $v = (v_1, v_2, \dots, v_N)^T$ be the positive eigenvector of the $(N \times N)$ -matrix $\tilde{A}\tilde{B}$ corresponding to the eigenvalue $\tilde{\rho} = \rho(\tilde{A}\tilde{B})$. By denoting $w = \tilde{B}v \in \mathbb{R}^M$ we obtain that $\tilde{\rho}v = \tilde{A}w$. Let us show that in this case

$$\tilde{\rho}v \leq Aw \quad \text{for all } A \in \mathcal{A}. \quad (14)$$

Otherwise, by Lemma 4(ii) there would exist a matrix $\bar{A} \in \mathcal{A}$ such that $\tilde{\rho}v \geq \bar{A}w$ and $\tilde{\rho}v \neq \bar{A}w$ which implies, by the definition of the vector w , that $\tilde{\rho}v \geq \bar{A}\tilde{B}v$ and $\tilde{\rho}v \neq \bar{A}\tilde{B}v$. Then by Lemma 3 $\rho(\bar{A}\tilde{B}) < \tilde{\rho} = \rho(\tilde{A}\tilde{B})$, which contradicts (12). This contradiction completes the proof of inequality (14).

Similarly, now we show that

$$w \geq Bv \quad \text{for all } B \in \mathcal{B}. \quad (15)$$

Again, assuming the contrary, by Lemma 4(i) there exists a matrix $\bar{B} \in \mathcal{B}$ such that $w \leq \bar{B}v$ and $w \neq \bar{B}v$. This last inequality, together with (14) applied to the matrix $A_{\bar{B}}$, yields $\tilde{\rho}v \leq A_{\bar{B}}\bar{B}v$ and $\tilde{\rho}v \neq A_{\bar{B}}\bar{B}v$. Then by Lemma 3

$$\tilde{\rho} < \rho(A_{\bar{B}}\bar{B}),$$

which contradicts (13) asserting that $\tilde{\rho} = \rho(\tilde{A}\tilde{B})$ is the maximum value of the function $\rho(A_B B)$ over all $B \in \mathcal{B}$. This contradiction completes the proof of inequality (15).

From (14) and (15) we obtain the inequality $\tilde{\rho}v \geq \tilde{A}Bv$ valid for all $B \in \mathcal{B}$, which by Lemma 3 implies the relations

$$\rho(\tilde{A}\tilde{B}) = \tilde{\rho} \geq \rho(\tilde{A}B)$$

valid for all $B \in \mathcal{B}$, or, what is the same, inequality (11). The theorem is proved for positive matrices.

Consider now the general case of compact IRU-sets of **non-negative matrices** \mathcal{A} and \mathcal{B} . If the set \mathcal{A} is determined by some sets of M -rows \mathcal{A}_i , $i = 1, 2, \dots, N$, then choose an arbitrary $\varepsilon > 0$ and consider the sets of rows

$$\mathcal{A}_i^{(\varepsilon)} = \{a^{(\varepsilon)} \mid a^{(\varepsilon)} = a + \varepsilon[1, 1, \dots, 1], a \in \mathcal{A}_i\},$$

where $i = 1, 2, \dots, N$. In this case the IRU-set of matrices $\mathcal{A}^{(\varepsilon)}$ consists of strictly positive matrices $A + \varepsilon\mathbf{1}$, where $A \in \mathcal{A}$ and $\mathbf{1}$ is the matrix with all elements equal to 1. Define similarly the IRU-set of matrices $\mathcal{B}^{(\varepsilon)}$.

By the result just proved, for each $\varepsilon > 0$ the minimax equality holds for positive matrices:

$$\min_{A \in \mathcal{A}^{(\varepsilon)}} \max_{B \in \mathcal{B}^{(\varepsilon)}} \rho(AB) = \max_{B \in \mathcal{B}^{(\varepsilon)}} \min_{A \in \mathcal{A}^{(\varepsilon)}} \rho(AB),$$

which by Lemma 5 is equivalent to the existence of $\tilde{A}_\varepsilon \in \mathcal{A}$ and $\tilde{B}_\varepsilon \in \mathcal{B}$ such that

$$\rho((\tilde{A}_\varepsilon + \varepsilon\mathbf{1})(B + \varepsilon\mathbf{1})) \leq \rho((\tilde{A}_\varepsilon + \varepsilon\mathbf{1})(\tilde{B}_\varepsilon + \varepsilon\mathbf{1})) \leq \rho((A + \varepsilon\mathbf{1})(\tilde{B}_\varepsilon + \varepsilon\mathbf{1}))$$

for all $A \in \mathcal{A}$ and $B \in \mathcal{B}$. Taking here $\varepsilon = \varepsilon_n$, where $\{\varepsilon_n\}$ is an arbitrary sequence of positive numbers converging to zero, we get

$$\rho((\tilde{A}_{\varepsilon_n} + \varepsilon_n\mathbf{1})(B + \varepsilon_n\mathbf{1})) \leq \rho((\tilde{A}_{\varepsilon_n} + \varepsilon_n\mathbf{1})(\tilde{B}_{\varepsilon_n} + \varepsilon_n\mathbf{1})) \leq \rho((A + \varepsilon_n\mathbf{1})(\tilde{B}_{\varepsilon_n} + \varepsilon_n\mathbf{1})) \quad (16)$$

for all $A \in \mathcal{A}$ and $B \in \mathcal{B}$. Without loss of generality, in view of the compactness of the sets \mathcal{A} and \mathcal{B} , we may assume the existence of matrices \tilde{A} and \tilde{B} such that $\tilde{A}_{\varepsilon_n} \rightarrow \tilde{A} \in \mathcal{A}$ and $\tilde{B}_{\varepsilon_n} \rightarrow \tilde{B} \in \mathcal{B}$ as $n \rightarrow \infty$. Then turning to the limit in (16), we obtain the inequalities $\rho(\tilde{A}B) \leq \rho(\tilde{A}\tilde{B}) \leq \rho(A\tilde{B})$ for all $A \in \mathcal{A}$ and $B \in \mathcal{B}$, which are equivalent to (11) and (12). This concludes the proof. \square

Corollary 1. *For IRU-sets \mathcal{A} and \mathcal{B} of non-negative matrices it holds that*

$$\text{mm}(\text{conv}(\mathcal{A}), \text{conv}(\mathcal{B})) = \text{mm}(\mathcal{A}, \mathcal{B}).$$

Proof. We denote $V = \text{mm}(\mathcal{A}, \mathcal{B})$ and $V' = \text{mm}(\text{conv}(\mathcal{A}), \text{conv}(\mathcal{B}))$. Then

$$V' \stackrel{1}{=} \min_{A \in \text{conv}(\mathcal{A})} \max_{B \in \text{conv}(\mathcal{B})} \rho(BA) \stackrel{2}{\leq} \min_{A \in \mathcal{A}} \max_{B \in \text{conv}(\mathcal{B})} \rho(BA) \stackrel{3}{=} \min_{A \in \mathcal{A}} \max_{B \in \mathcal{B}} \rho(BA) = V,$$

where 1 follows from identity (2), 2 from the inclusion $\mathcal{A} \subseteq \text{conv}(\mathcal{A})$, 3 from Lemma 1 and equalities (6). Symmetrically,

$$V' = \max_{B \in \text{conv}(\mathcal{B})} \min_{A \in \text{conv}(\mathcal{A})} \rho(AB) \geq \max_{B \in \mathcal{B}} \min_{A \in \text{conv}(\mathcal{A})} \rho(AB) = \max_{B \in \mathcal{B}} \min_{A \in \mathcal{A}} \rho(AB) = V,$$

which concludes the proof. \square

5 Solving the games

5.1 Solving matrix multiplication games

Theorem 2. *Let \mathcal{A} and \mathcal{B} be compact IRU-sets of non-negative matrices. Then the corresponding MMG is determined, moreover Adam and Eve possess constant optimal strategies.*

Proof. Let us apply Theorem 1 to matrix sets \mathcal{A} and \mathcal{E} . Define V , E_0 and A_0 such that

$$\min_{E \in \mathcal{E}} \rho(EA_0) = \max_{A \in \mathcal{A}} \min_{E \in \mathcal{E}} \rho(EA) = \min_{E \in \mathcal{E}} \max_{A \in \mathcal{A}} \rho(EA) = \max_{A \in \mathcal{A}} \rho(E_0A) = V. \quad (17)$$

Let Adam only play A_0 . Take any compatible play $\pi = A_0E_1A_0E_2 \cdots$ and put $C_i = A_0E_i$. Denote $\mathcal{C} = \{EA_0 | E \in \mathcal{E}\}$, it is an IRU-set by Lemma 1. The payoff P for π yields

$$\begin{aligned} P &= \limsup_{n \rightarrow \infty} \|A_0C_1 \cdots C_{n-1}E_n\|^{1/n} \leq \limsup_{n \rightarrow \infty} (\|A_0\| \cdot \|C_1 \cdots C_{n-1}\| \cdot \|E_n\|)^{1/n} \\ &\leq \lim_{n \rightarrow \infty} K^{\frac{2}{n}} \limsup_{n \rightarrow \infty} \|C_1 \cdots C_{n-1}\|^{\frac{1}{n-1}} \leq \hat{\rho}(\mathcal{C}) \stackrel{1}{=} \max_{C \in \mathcal{C}} \rho(C) = \max_{E \in \mathcal{E}} \rho(EA_0) \stackrel{2}{=} V, \end{aligned}$$

where the constant K is an upper bound for the norms of the matrices in \mathcal{A} and \mathcal{E} , equality 1 comes from the first equality (5) and equality 2 comes from (17).

Let Eve only play E_0 . Take any compatible play $\pi' = A_1E_0A_2E_0 \cdots$. Let us write $D_i = A_iE_0$. Denote $\mathcal{D} = \{AE_0, A \in \mathcal{A}\}$, it is an IRU-set. The payoff P' for π' is such that

$$P' = \limsup_{n \rightarrow \infty} \|C_1 \cdots C_n\|^{1/n} \geq \liminf_{n \rightarrow \infty} \|C_1 \cdots C_n\|^{1/n} \geq \check{\rho}(\mathcal{D}) \stackrel{1}{=} \min_{D \in \mathcal{D}} \rho(D) = \min_{A \in \mathcal{A}} \rho(AE_0) \stackrel{2}{=} V,$$

where equality 1 comes from the second equality (5) and equality 2 from (17) using (2).

We have proved that Adam (by playing constantly A_0) can ensure payoff $\leq V$ whatever Eve plays; and that Eve (by playing constantly E_0) can ensure payoff $\geq V$ whatever Adam plays. This concludes the proof. \square

Corollary 2. *Let \mathcal{A} and \mathcal{E} be compact IRU-sets of non-negative matrices. In the MMG on $\text{conv}(\mathcal{A}), \text{conv}(\mathcal{E})$, the constant optimal strategies can be chosen from sets \mathcal{A} and \mathcal{E} .*

This is immediate from the proof of the theorem and Corollary 1.

5.2 Solving entropy games

In this section, we consider an EG on an arena \mathbf{A} and the corresponding matrix sets \mathcal{A} and \mathcal{E} , as defined in Section 3.3.

Lemma 6. *Let (σ, τ) be two positional strategies in the EG. Then, if corresponding constant strategies A_σ and E_τ are optimal for their respective players in the MMG with matrix sets $\text{conv}(\mathcal{A})$ and $\text{conv}(\mathcal{E})$, then so are σ and τ .*

Proof. Let σ' and τ' be arbitrary strategies in the EG, then by Lemma 2 to the strategy pair (σ', τ) corresponds (ζ', E_τ) with some strategy ζ' having the same value in the MMG. Symmetrically to (σ, τ') corresponds some pair (A_σ, θ') . We have:

$$P(\sigma', \tau) = P(\zeta', E_\tau) \leq P(A_\sigma, E_\tau) = P(\sigma, \tau) = P(A_\sigma, E_\tau) \leq P(A_\sigma, \theta') = P(\sigma, \tau'),$$

where the equalities come from Lemma 2 and the inequalities from the optimality of E_τ and A_σ , respectively. Thus σ and τ are optimal. \square

Theorem 3. *Every EG is determined, and Despot and Tribune possess positional optimal strategies.*

Proof. From Theorem 2, we have that for the MMG $(\text{conv}(\mathcal{A}), \text{conv}(\mathcal{E}))$ both Adam and Eve possess constant optimal strategies by playing constantly some matrices A and E . From Corollary 2, the matrices A and E can be chosen respectively in sets \mathcal{A} and \mathcal{E} . Then, there exist positional strategies σ and τ on \mathbf{A} such that $A = A_\sigma$ and $E = E_\tau$. By Lemma 6, strategies σ and τ are optimal in the EG. \square

Back to the running example. Here a quick exploration of the combinations of rows shows that the matrices realizing the min-max over the two IRU-sets defined by row sets $\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3$ and $\mathcal{B}_1, \mathcal{B}_2, \mathcal{B}_3$ are $A = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix}$ for Adam/Despot and $B = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}$ for Eve/Tribune, describing both the optimal constant strategy of the MMG and the optimal positional strategy of the EG induced by this arena. The value of both games is the spectral radius $\rho(AB) = \rho\left(\begin{bmatrix} 2 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 2 \end{bmatrix}\right) = (\sqrt{17} + 3)/2 \simeq 3.56155281280883$.

5.3 Complexity issues

We will analyze complexity of solving matrix multiplication (and hence entropy) game. Let us start with necessary and sufficient conditions for inequalities on joint spectral radii and subradii of IRU-sets (recall also (5) relating them to maximal and minimal spectral radii).

Lemma 7. *Let \mathcal{A} be a compact IRU-set of positive $(N \times N)$ -matrices.*

- (i) *If $\tilde{A} \in \mathcal{A}$ is a matrix satisfying $\rho(\tilde{A}) = \check{\rho}(\mathcal{A})$ and \tilde{v} is its positive eigenvector corresponding to the eigenvalue $\rho(\tilde{A})$, then $A\tilde{v} \geq \check{\rho}(\mathcal{A})\tilde{v}$ for all $A \in \mathcal{A}$.*
- (ii) *If $\tilde{A} \in \mathcal{A}$ is a matrix satisfying $\rho(\tilde{A}) = \hat{\rho}(\mathcal{A})$ and \tilde{v} is its positive eigenvector corresponding to the eigenvalue $\rho(\tilde{A})$, then $A\tilde{v} \leq \hat{\rho}(\mathcal{A})\tilde{v}$ for all $A \in \mathcal{A}$.*

Proof. To prove (i) let us note that $\tilde{A}\tilde{v} = \check{\rho}(\mathcal{A})\tilde{v}$. Then by Lemma 4)i) either $A\tilde{v} \geq \check{\rho}(\mathcal{A})\tilde{v}$ for all $A \in \mathcal{A}$ or there exists a matrix $\tilde{A} \in \mathcal{A}$ such that $\tilde{A}\tilde{v} \leq \check{\rho}(\mathcal{A})\tilde{v}$ and $\tilde{A}\tilde{v} \neq \check{\rho}(\mathcal{A})\tilde{v}$. In the latter case, by Lemma 3 the inequality $\rho(\tilde{A}) < \check{\rho}(\mathcal{A})$ would hold, which contradicts to the definition of $\check{\rho}(\mathcal{A})$. Hence, the inequality $A\tilde{v} \geq \check{\rho}(\mathcal{A})\tilde{v}$ holds for all $A \in \mathcal{A}$, q.e.d. Assertion (ii) is proved similarly. \square

Lemma 8. *For any compact IRU-set of positive matrices \mathcal{A} and $\alpha \in \mathbb{Q}_+$ the following equivalences hold:*

$$\hat{\rho}(\mathcal{A}) < \alpha \Leftrightarrow \exists v > 0 \forall A \in \mathcal{A} (Av < \alpha v); \quad (18)$$

$$\hat{\rho}(\mathcal{A}) \leq \alpha \Leftrightarrow \exists v > 0 \forall A \in \mathcal{A} (Av \leq \alpha v); \quad (19)$$

$$\check{\rho}(\mathcal{A}) > \alpha \Leftrightarrow \exists v > 0 \forall A \in \mathcal{A} (Av > \alpha v); \quad (20)$$

$$\check{\rho}(\mathcal{A}) \geq \alpha \Leftrightarrow \exists v > 0 \forall A \in \mathcal{A} (Av \geq \alpha v). \quad (21)$$

If the matrices are only non-negative, the equivalences (18) above and (22) below hold:

$$\check{\rho}(\mathcal{A}) \geq \alpha \Leftrightarrow \exists (v \geq 0, v \neq 0) \forall A \in \mathcal{A} (Av \geq \alpha v). \quad (22)$$

Proof. For positive matrices, implications \Leftarrow follow from Lemma 3. As for \Rightarrow , it suffices to take v the eigenvector of the matrix $\tilde{A} \in \mathcal{A}$ with the largest (smallest) eigenvalue, and to apply Lemma 7.

As for non-negative matrices, we have four implications to prove:

(18), \Rightarrow Denote, for any $\varepsilon > 0$, $\mathcal{A}_\varepsilon = \{A + \varepsilon \mathbf{1} \mid A \in \mathcal{A}\}$. If $\hat{\rho}(\mathcal{A}) < \alpha$ then due to compactness of the set \mathcal{A} there exists $\varepsilon > 0$ such that $\hat{\rho}(\mathcal{A}_\varepsilon) = \hat{\rho}(\mathcal{A} + \varepsilon \mathbf{1}) < \alpha$. Then by (18) (already proved for positive matrices), there exists $v > 0$ such that $(A + \varepsilon \mathbf{1})v < \alpha v$ for all $A \in \mathcal{A}$. Since $Av \leq (A + \varepsilon \mathbf{1})v$, then $Av < \alpha v$ for all $A \in \mathcal{A}$, q.e.d.

(18), \Leftarrow Suppose there exists $v > 0$ such that $Av < \alpha v$ for all $A \in \mathcal{A}$. Then due to compactness of the set \mathcal{A} there exists $\varepsilon > 0$ such that $(A + \varepsilon \mathbf{1})v < \alpha v$ for all $A \in \mathcal{A}$. Therefore by (18) (for positive matrices) $\hat{\rho}(\mathcal{A} + \varepsilon \mathbf{1}) < \alpha$, and hence by (1) we obtain $\hat{\rho}(\mathcal{A}) < \alpha$, q.e.d.

(22), \Rightarrow Let $\check{\rho}(\mathcal{A}) \geq \alpha$ then by (1) it holds that $\check{\rho}(\mathcal{A} + \varepsilon \mathbf{1}) \geq \alpha$ for any $\varepsilon > 0$. Then by (21) (for positive matrices) for any $\varepsilon > 0$ exists a vector $v_\varepsilon > 0$ such that $\|v_\varepsilon\| = 1$ and

$$(A + \varepsilon \mathbf{1})v_\varepsilon \geq \alpha v_\varepsilon \quad (23)$$

for all $A \in \mathcal{A}$. Choose a sequence $\varepsilon_n \rightarrow 0$ for which the corresponding vectors v_{ε_n} converge to some vector $v \geq 0$ (let us point out that $\|v\| = 1$ and so it is non-zero). Then passing to the limit in (23) we obtain $Av \geq \alpha v$ for all $A \in \mathcal{A}$, q.e.d.

(22), \Leftarrow Suppose there exists a non-zero vector $v \geq 0$ such that $Av \geq \alpha v$ for all $A \in \mathcal{A}$. Then by Lemma 3, $\rho(A) \geq \alpha$ for all $A \in \mathcal{A}$ and hence $\check{\rho}(\mathcal{A}) \geq \alpha$, q.e.d. \square

Computational aspects of calculating the values $\hat{\rho}(\mathcal{A})$ and $\check{\rho}(\mathcal{A})$ for IRU-sets of non-negative matrices, based on relations (5), are discussed in [4, 14, 15]. These articles provide polynomial algorithms for approximation of the minimal and maximal spectral radii, as well as a variant of simplex method for these problems. In the next theorem we prove a complexity result in a form suitable for game analysis.

Theorem 4. *Given a finite IRU-set of nonnegative matrices \mathcal{A} with rational elements (represented by row sets $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_N$), and a number $\alpha \in \mathbb{Q}_+$, the decision problems whether $\hat{\rho}(\mathcal{A}) < \alpha$ and whether $\check{\rho}(\mathcal{A}) \geq \alpha$ belong to the complexity class P. Moreover, if the matrices are positive, then the decision problems $\hat{\rho}(\mathcal{A}) \leq \alpha$ and $\check{\rho}(\mathcal{A}) > \alpha$ are also in P.*

Proof. The polynomial algorithms are based on the previous lemma. Consider the problem of deciding $\hat{\rho}(\mathcal{A}) < \alpha$, which can be rewritten using (18) as $\exists v > 0 \forall A \in \mathcal{A} (Av < \alpha v)$. We will not test all the matrices $A \in \mathcal{A}$ (there are exponentially many of them), instead we will treat each row separately. The condition $\forall A \in \mathcal{A} (Av < \alpha v)$ can be rewritten as a system of linear inequalities: for each i and for each row $[c_1, c_2, \dots, c_N] \in \mathcal{A}_i$ require that

$$c_1 v_1 + c_2 v_2 + \dots + c_N v_N < \alpha v_i.$$

The condition $v > 0$ can be written as N inequalities $v_i > 0$: one for each coordinate. Using a polynomial algorithm for linear programming we can decide whether a solution v satisfying all these linear inequalities exists.

All other decision procedures, based on (19)–(22), are similar. The condition $v \geq 0, v \neq 0$ should be represented as disjunction of N linear systems $v_j > 0 \wedge \bigwedge_{i=1}^N v_i \geq 0$. \square

Theorem 5. *Given two finite IRU-sets of nonnegative matrices \mathcal{A} and \mathcal{B} with rational elements, and a number $\alpha \in \mathbb{Q}_+$, the decision problems of whether $\mathbf{mm}(\mathcal{A}, \mathcal{B}) < \alpha$ and whether $\mathbf{mm}(\mathcal{A}, \mathcal{B}) \geq \alpha$ belong to $\mathbf{NP} \cap \mathbf{coNP}$.*

Moreover, if the matrices are positive, then the decision problems of whether $\mathbf{mm}(\mathcal{A}, \mathcal{B}) \leq \alpha$ and whether $\mathbf{mm}(\mathcal{A}, \mathcal{B}) > \alpha$ are also in $\mathbf{NP} \cap \mathbf{coNP}$.

Proof. Consider the problem of deciding whether $\mathbf{mm}(\mathcal{A}, \mathcal{B}) < \alpha$, which can be rewritten as

$$\min_{A \in \mathcal{A}} \max_{B \in \mathcal{B}} \rho(BA) < \alpha \Leftrightarrow \exists A_0 \in \mathcal{A} (\hat{\rho}(\mathcal{B}A_0) < \alpha).$$

The nondeterministic polynomial algorithm proceeds as follows:

- guess non-deterministically a matrix $A_0 \in \mathcal{A}$;
- compute the representation of $\mathcal{B}A_0$ as an IRU-set generated by the row sets $\mathcal{C}_1, \mathcal{C}_2, \dots, \mathcal{C}_N$;
- check the inequality $\hat{\rho}(\mathcal{B}A_0) < \alpha$ in polynomial time using Theorem 4.

We conclude that the problem $\mathbf{mm}(\mathcal{A}, \mathcal{B}) < \alpha$ is in NP. The complementary problem $\mathbf{mm}(\mathcal{A}, \mathcal{B}) \geq \alpha$ is also in NP, as it can be rewritten as

$$\max_{B \in \mathcal{B}} \min_{A \in \mathcal{A}} \rho(AB) \geq \alpha \Leftrightarrow \exists B_0 \in \mathcal{B} (\check{\rho}(\mathcal{A}B_0) \geq \alpha),$$

and decided by a non-deterministic polynomial algorithm similarly. We conclude that the two problems belong to $\mathbf{NP} \cap \mathbf{coNP}$.

For positive matrices, proofs for two other decision problems based on the second statement of Theorem 4 are similar. \square

Our main complexity result follows immediately.

Theorem 6. *Given an EG or an MMG with finite IRU-sets of non-negative matrices with rational elements and $\alpha \in \mathbb{Q}_+$, the decision problems for its value: $V < \alpha$ and $V \geq \alpha$ belong to $\text{NP} \cap \text{coNP}$.*

6 Related models

6.1 Weighted entropy games

Up to now we have considered entropy games with *simple* transitions, but it is straightforward to add multiplicities (weights) to them. A *weighted entropy game* is played on a *weighted arena* $\mathbf{A} = (D, T, \Sigma, \Delta, w)$ with a function $w : \Delta \rightarrow \mathbb{N}_+$ assigning weights to transitions (informally a weight is the number of ways in which a transition can be taken). Strategies and plays are defined as in the unweighted case. Let L be some set of (infinite) plays. For every $u \in \text{pref}(L)$ we define its weight $w(u)$ as the product of weights of all the transitions taken along u . We define $w_n(L) = \sum_{u \in \text{pref}_{4n}(L)} w(u)$, and finally the payoff corresponding to strategies σ and τ of two players is defined as:

$$P = \limsup_{n \rightarrow \infty} (w_n(L(\sigma, \tau)))^{1/n}.$$

Our main results on EGs (Theorems 3 and 6) extend straightforwardly to weighted EGs.

6.2 Mean-payoff games

Well-known mean-payoff finite-state games (MPG) [9] can be considered as a deterministic subclass of weighted entropy games. A (variant of) MPG is played on arena (D, T, Δ, w) with transition relation $\Delta \subseteq D \times T \cup T \times D$ and weight function $w : \Delta \rightarrow \mathbb{N}$. The play starts in some state $d_0 \in D$, and the two players choose transitions in turns. The resulting play is an infinite word $\gamma_{d_0} \in (D \cdot T)^\omega$. The mean-payoff corresponding to the play $\gamma_{d_0} = d_0, t_0, d_1, t_1, \dots$ is the limit of the average weight of transitions taken:

$$\text{mp}(\gamma_{d_0}) = \limsup_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n (w(d_{i-1}, t_{i-1}) + w(t_{i-1}, d_i)).$$

Finally, player D wants to minimize and player T to maximize the payoff $\max_{d_0 \in D} \text{mp}(\gamma_{d_0})$. As proved in [9], MPGs are determined and their optimal strategies are positional. As for complexity, [21] shows that testing whether the value of an MPG is smaller than a rational α is in $\text{NP} \cap \text{coNP}$ and becomes polynomial for weights presented in unary system.

An MPG $\mathbf{A} = (D, T, \Delta, w)$ can be transformed into a weighted EG $\mathbf{A}' = (D, T, \Sigma, \Delta', w')$ as follows. The states of both players are the same, Σ is large enough, and to each transition $(p, q) \in \Delta$ corresponds a transition $(p, a, q) \in \Delta'$ with some a (occurring only in this transition). Its weight is $w'(p, a, q) = 2^{w(p, q)}$. We notice that the EG obtained is deterministic: due to unique transition labels for any strategies σ and τ the language $L(\sigma, \tau)$ contains one play for each initial state. Strategies and plays of both games \mathbf{A} and \mathbf{A}' are now in natural bijection and payoff of \mathbf{A} equals the logarithm of the payoff of \mathbf{A}' .

This way, we obtain the classical results that MPGs are determined and both players have optimal positional strategies. The complexity obtained using our approach is, however, not as good as using direct algorithms, see [21].

6.3 Population dynamics

Consider an EG with arena $\mathbf{A} = (D, T, \Sigma, \Delta)$. It can be interpreted as the following population game between two players, Damien and Theo. Elements of D and T correspond to species (forms of viruses, microorganisms, etc.). Initially there is one (or any non-zero number of) organism(s) for each species in D . At his turn Damien chooses an action $a \in \Sigma$ and applies it to each organism. An

organism of species d , when subject to action a , turns into the set of organisms $\{t \mid (d, a, t) \in \Delta\}$. Theo plays similarly. The aim of Damien is to minimize the growth rate of the population, Theo wants to maximize it. It is easy to see that the value of the game and the optimal (positional) strategies are the same as for the EG.

7 Conclusions

We have introduced two (closely interrelated) families of games: entropy games played on finite arenas (graphs), and matrix multiplication games. The main result is that entropy games are determined and optimal strategies are positional in EG, while MMGs for IRU-sets of non-negative matrices are determined and optimal strategies are constant. These results are based on a novel minimax theorem on spectral radii of products of IRU-sets of matrices. The results obtained prove the existence of equilibria in zero-sum games with a novel type of limit payoffs which is neither computed on a single play of the game nor probabilistic. On the other hand, they rely upon and generalize important results on the computability of joint spectral radii and subradii, an important problem in switching dynamic systems.

A presumably straightforward extension would be the “probabilization” of our game models, in that both Despot and Tribune would be allowed to play randomized strategies. The minimax theorem ensures the existence of optimal pure strategies for both players. However the entropy-based payoff of the game needs to be given a proper generalization to this probabilistic setting. We may mention that such a generalization could be seen as entropy games on probabilistic branching processes, and provide interesting links with this research domain.

Finally, both our games are turn-based games with perfect information, as Despot and Tribune (resp. Adam and Eve) play one after the other and both know exactly the current state of the system. The first generalization to be considered is to go to synchronous games – where perhaps some polynomial-size memory is needed, similarly to the classic case of synchronous games played on graphs in infinite time. The more difficult case is that of games of imperfect information. It should be noted that corresponding matrix games do not have any more the simple structure (independent row uncertainty), and we conjecture that analysis of such games is non-computable.

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A Some proofs

Proof of Lemma 1. (i) Let \mathcal{A}_i be the set of admissible i -th rows in \mathcal{A} ,

$$\mathcal{R}_i = \left\{ \left[\sum_{k=1}^n a_k b_{kj} \right]_{1 \leq j \leq n} \mid a \in \mathcal{A}_i \right\}$$

and \mathcal{R} be the IRU-set made from sets \mathcal{R}_i . One has that $\mathcal{A}B = \mathcal{R}$:

- if $M \in \mathcal{R}$ then, let $a^{(i)} \in \mathcal{A}_i$ be such that the i -th row of M is $\left[\sum_{k=1}^n a_k^{(i)} b_{kj} \right]_{1 \leq j \leq n}$, then $M = AB$ where A is the matrix made with rows a_i ;
 - conversely, if $A \in \mathcal{A}$ and $a^{(i)}$ is the i -th row of A , then the i -th row of AB equals $\left[\sum_{k=1}^n a_k^{(i)} b_{kj} \right]_{1 \leq j \leq n}$ and belongs to \mathcal{R}_i .
- (ii) The easy direction is \subseteq . Let M be a matrix of $\text{conv}(\mathcal{A})$. Then, there exist matrices $M_1, \dots, M_k \in \mathcal{A}$ and real numbers $\lambda_1, \dots, \lambda_k$ such that

$$M = \sum_{i=1}^k \lambda_i M_i.$$

Let j be an integer in $\{1, \dots, n\}$. For all $i \in \{1, \dots, k\}$, there exists a vector $v_i \in \mathcal{A}_j$ such that row j of M_i is v_i . Then, row j of M being $\sum_{i=1}^k \lambda_i v_i$, it belongs to $\text{conv} \mathcal{A}_j$.

For the direction \supseteq , let M be a matrix of the IRU-set formed by $\text{conv}(\mathcal{A}_1), \dots, \text{conv}(\mathcal{A}_n)$. Let u_1, \dots, u_n be the rows of the matrix M . By definition of M , there are integers k_i for $i \in \{1, \dots, n\}$, real numbers $\lambda_j^i \in [0, 1]$ and vectors $v_j^i \in \mathcal{A}_i$ for $i \in \{1, \dots, n\}$ and $j \in \{1, \dots, k_i\}$ such that

$$u_i = \sum_{j=1}^{k_i} \lambda_j^i v_j^i \text{ and } \sum_{j=1}^{k_i} \lambda_j^i = 1.$$

Then, for all $i \in \{1, \dots, n\}$, one has:

$$u_i = \sum_{j_i=1}^{k_i} \lambda_{j_i}^i v_{j_i}^i = \left(\prod_{l=1}^{i-1} \sum_{j_l=1}^{k_l} \lambda_{j_l}^l \right) \left(\sum_{j_i=1}^{k_i} \lambda_{j_i}^i v_{j_i}^i \right) \left(\prod_{l=i+1}^n \sum_{j_l=1}^{k_l} \lambda_{j_l}^l \right) = \sum_{j_1=1}^{k_1} \dots \sum_{j_n=1}^{k_n} \left(\prod_{l=1}^n \lambda_{j_l}^l \right) v_{j_i}^i.$$

Hence

$$M = \begin{bmatrix} u_1 \\ \vdots \\ u_n \end{bmatrix} = \sum_{j_1=1}^{k_1} \dots \sum_{j_n=1}^{k_n} \left(\prod_{l=1}^n \lambda_{j_l}^l \right) \begin{bmatrix} v_{j_1}^1 \\ \vdots \\ v_{j_n}^n \end{bmatrix}.$$

each matrix in the sum being in \mathcal{A} . The proof is finished stating that

$$\sum_{j_1=1}^{k_1} \dots \sum_{j_n=1}^{k_n} \prod_{l=1}^n \lambda_{j_l}^l = \prod_{l=1}^n \sum_{j_l=1}^{k_l} \lambda_{j_l}^l = 1.$$

- (iii) Immediate from the characterization of compact sets (of finite dimension) as bounded and closed. \square

Proof of Lemma 3. As stated in [11, Corollary 8.1.29], for any nonnegative matrix A and $u > 0$

$$\alpha u \leq Au \leq \beta u \Rightarrow \alpha \leq \rho(A) \leq \beta, \quad (24)$$

our statement (i) is now immediate. Let us prove the three remaining assertions.

- (ii) Let $Au \leq \rho u$ for $u > 0$ with $A > 0$ and $Au \neq \rho u$. Then at least one coordinate of the vector $Au - \rho u \leq 0$ is strictly negative. Therefore the condition $A > 0$ implies strict negativity of all coordinates of the vector $A(Au - \rho u)$. Then there exists $\varepsilon > 0$ such that $A(Au - \rho u) \leq -\varepsilon u$ and therefore $A^2u = A(Au - \rho u) + \rho Au \leq (\rho^2 - \varepsilon)u$. Then, by (24), we get $\rho(A^2) \leq \rho^2 - \varepsilon$, and thus $\rho(A) \leq \sqrt{\rho^2 - \varepsilon} < \rho$, q.e.d.
- (iii) The condition $Au \geq \rho u$ with non-zero $u \geq 0$ implies $A^n u \geq \rho^n u$ for any $n \geq 1$. Then $\|A^n\| \cdot \|u\| \geq \|A^n u\| \geq \rho^n \|u\|$. Therefore $\|A^n\| \geq \rho^n$, and by Gelfand's formula $\rho(A) \geq \rho$, q.e.d.
- (iv) Now let $A > 0$ and $Au \neq \rho u$. Then at least one coordinate of the vector $Au - \rho u \geq 0$ is strictly positive. Therefore the condition $A > 0$ implies strict positivity of all the coordinates of the vector $A(Au - \rho u)$. Then there exists $\varepsilon > 0$ such that $A(Au - \rho u) \geq \varepsilon u$ and therefore $A^2u = A(Au - \rho u) + \rho Au \geq (\rho^2 + \varepsilon)u$. This, by (iii) applied to the matrix A^2 , implies $\rho(A^2) \geq \rho^2 + \varepsilon$, and thus $\rho(A) \geq \sqrt{\rho^2 + \varepsilon} > \rho$, q.e.d. \square