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ON THE STABILITY OF PRODUCTS OF STOCHASTIC MATRICES

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On the Stability of Products of Stochastic Matrices *)

by

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ABSTRACT.

This paper considers a finite set of stochastic matrices of finite order. Conditions will be given under which any product of matrices from this set converges to a constant stochastic matrix. Also, it will be shown that the convergence is exponentially fast.

KEY WORDS & PHRASES: *Stochastic matrices, products, exponential convergence.*

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*) This paper is not for review; it is meant for publication elsewhere.

1. INTRODUCTION

This paper deals with a finite set $\mathcal{P}$ of $N \times N$ stochastic matrices, i.e., for each $P = (p_{ij}) \in \mathcal{P}$, $p_{ij} \geq 0$ and $\Sigma_{j=1}^{N} p_{ij} = 1$ for all $i,j = 1,\ldots,N$. Non-homogeneous Markov chains were studied amongst others in [3], [4] and [7], see also [5] and [6].

Consider the following condition introduced in WOLFOWITZ [7].

C1. For each integer $k \geq 1$ and any $P_i \in \mathcal{P}(1 \leq i \leq k)$ the stochastic matrix $P_k \ldots P_1$ is aperiodic and has a single ergodic class.

This conditon is equivalent to each of the following two conditions.

C2. There is an integer $\nu \geq 1$ such that for each $k \geq \nu$ and any $P_i \in \mathcal{P}(1 \leq i \leq k)$ the matrix $P_k \ldots P_1$ is scrambling, i.e. any two rows of $P_k \ldots P_1$ have a positive entry in a same column (cf.[3]).

C3. There is an integer $\mu \geq 1$ such that for each $k \geq \mu$ and any $P_i \in \mathcal{P}(1 \leq i \leq k)$ the matrix $P_k \ldots P_1$ has a column with only positive entries.

We remark that in C2(C3) it suffices to require the condition imposed on the matrix products only for those of length $\nu(\mu)$. The equivalencies C1 $\Leftrightarrow$ C2 $\Leftrightarrow$ C3 can be seen as follows. Using the fact that a stochastic matrix Q such that Q^n is scrambling for some $n \geq 1$ is aperiodic and has a single ergodic class, we have C3 $\Rightarrow$ C2 $\Rightarrow$ C1. WOLFOWITZ [7] proved that C1 $\Rightarrow$ C2. However, an examination of the proof of Lemma 3 in [7] shows that this lemma remains true when we replace its conclusion that P_1 is scrambling by the conclusion that P_1 has a column with only positive entries. Using this, the proof of Lemma 4 in [7] next shows that C1 $\Rightarrow$ C3.

The purpose of this paper is to show that under C1 for any sequence $\{P_i, i \geq 1\}$ of matrices from $\mathcal{P}$ the matrix product $P_n \ldots P_1$ converges to a constant stochastic matrix as $n \to \infty$. Also, it will be shown that the convergence is exponentially fast. Further, we shall give conditions imposed on the individual matrices from $\mathcal{P}$ such that C1 holds. This paper may have applications amongst others in Markov decision theory (cf. BROWN [1]).

2. CONVERGENCE OF THE MATRIX PRODUCTS

The following theorem generalizes the Theorem in WOLFOWITZ [7] and is related to Theorem 2 in PAZ & REICHAW [4]. Theorem 1 below shows not only that under C1 for any sequence $\{P_i\}$ of matrices from $\mathcal{P}$ the product matrix $P_n \ldots P_1$ converges to a constant stochastic matrix as $n \to \infty$ but its proof which was suggested by the one given on pp. 173-174 in DOOB [2] shows also that the convergence is exponentially fast where the convergence rate is uniformly bounded in all sequences $\{P_i\}$.

THEOREM 1. *Suppose that* C1 *holds. Then there is an integer* $\nu \ge 1$, *a number* α *with* $0 \le \alpha < 1$ *and for any sequence* $\{P_i, i \ge 1\}$ *of matrices from* $\mathcal{P}$ *there is a probability distribution* $\{\pi_j, 1 \le j \le N\}$ *such that, for all* $i,j = 1,\ldots,N$,

$$|(P_n \ldots P_1)_{ij} - \pi_j| \le \alpha^{[n/\nu]} \quad \textit{for all } n \ge 1, \tag{1}$$

where $[x]$ *is the largest integer less than or equal to* x.

PROOF. We first introduce some notation. For any $N \times N$ stochastic matrix Q, let

$$\gamma(Q) = \min_{i_1,i_2} \sum_{j=1}^{N} \min(q_{i_1 j}, q_{i_2 j})$$

and, for $j = 1,\ldots,N$, let

$$M_j(Q) = \max_i q_{ij} \quad \text{and} \quad m_j(Q) = \min_i q_{ij}$$

Observe that $\gamma(Q) > 0$ if and only if Q is scrambling. By Lemma 4 in WOLFOWITZ [7], we can choose an integer $\nu \ge 1$ such that the matrix $P_\nu \ldots P_1$ is scrambling for any $P_i \in \mathcal{P}(1 \le i \le \nu)$. Then, by the finiteness of $\mathcal{P}$,

$$\gamma = \min\{\gamma(P_\nu \ldots P_1) \mid P_i \in \mathcal{P}(1 \le i \le \nu)\} > 0.$$

Now choose any sequence $\{P_i, i \ge 1\}$ of matrices from $\mathcal{P}$. For any $n \ge m \ge 1$, put for abbreviation $P_{n,m} = P_n \ldots P_m$. From $(P_{n+1,1})_{ij} = \Sigma_k (P_{n+1})_{ik} (P_{n,1})_{kj}$ it follows that for all $j = 1,\ldots,N$,

$$M_j(P_{n+1,1}) \le M_j(P_{n,1}) \quad \text{and} \quad m_j(P_{n+1,1}) \ge m_j(P_{n,1}) \quad \text{for all } n \ge 1. \tag{2}$$

Now, fix i,h and $n > \nu$. For any number a, let $a^+ = \max(a,0)$ and $a^- = -\min(a,0)$, so, $a = a^+ - a^-$ and $a^+, a^- \ge 0$. Using the fact that

$(a-b)^+ = a - \min(a,b)$ and that $\Sigma_1^N a_j^+ = \Sigma_1^N a_j^-$ when $\Sigma_1^N a_j = 0$, we get for any $j = 1,\dots,N$,

$$(P_{n,1})_{ij} - (P_{n,1})_{hj} = \sum_{k=1}^{N} \{(P_{n,n-\nu+1})_{ik} - (P_{n,n-\nu+1})_{hk}\} (P_{n-\nu,1})_{kj} =$$

$$= \sum_{k=1}^{N} \{(P_{n,n-\nu+1})_{ik} - (P_{n,n-\nu+1})_{hk}\}^+ (P_{n-\nu,1})_{kj} +$$

$$- \sum_{k=1}^{N} \{(P_{n,n-\nu+1})_{ik} - (P_{n,n-\nu+1})_{hk}\}^- (P_{n-\nu,1})_{kj} \le$$

$$\le \sum_{k=1}^{N} \{(P_{n,n-\nu+1})_{ik} - (P_{n,n-\nu+1})_{hk}\}^+ \{M_j(P_{n-\nu,1}) - m_j(P_{n-\nu,1})\} =$$

$$= \{1 - \sum_{k=1}^{N} \min[(P_{n,n-\nu+1})_{ik}, (P_{n,n-\nu+1})_{hk}]\} \{M_j(P_{n-\nu,1}) - m_j(P_{n-\nu,1})\} \le$$

$$\le (1-\gamma) \{M_j(P_{n-\nu,1}) - m_j(P_{n-\nu,1})\}.$$

Since i and h were arbitrarily chosen, it follows that for all $j = 1,\dots,N$

$$M_j(P_{n,1}) - m_j(P_{n,1}) \le (1-\gamma) \{M_j(P_{n-\nu,1}) - m_j(P_{n-\nu,1})\} \quad \text{for all } n > \nu$$

A repeated application of this inequality and the fact that $M_j(Q) - m_j(Q) \le 1$ for any stochastic matrix Q show that, for all $j = 1,\dots,N$,

(3) $$M_j(P_{n,1}) - m_j(P_{n,1}) \le (1-\gamma)^{[n/\nu]} \quad \text{for all } n \ge 1.$$

Together (2) and (3) prove that for any $j = 1,\dots,N$ there is a finite number $\pi_j \ge 0$ such that $M_j(P_{n,1})$ is monotone decreasing to π_j as $n \to \infty$ and $m_j(P_{n,1})$ is monotone increasing to π_j as $n \to \infty$. Next this result, inequality (3) and the definitions of M_j and m_j imply (1) with $\alpha = 1 - \gamma$. Clearly, $\Sigma\pi_j = 1$ since $P_n \dots P_1$ is a stochastic matrix for all n. □

By Theorem 4.7 on p. 90 in PAZ [5] the integer ν in condition C2 can always be taken less than or equal to $\nu^* = (1/2)\ (3^N - 2^{N+1} + 1)$. Hence, by

C1 $\Leftrightarrow$ C2, it is decidable whether C1 holds by checking all matrix products of at most length ν^*. This may be practically impossible when N is large. We shall now discuss conditions imposed on the individual matrices from $\mathcal{P}$ such that C1 holds. Before doing this, we first remark that it was pointed out on p. 235 in HAJNAL [3] that C1 does not generally hold when each $P \in \mathcal{P}$ is aperiodic and has a single ergodic class. Clearly, C1 holds when each $P \in \mathcal{P}$ is scrambling since in that case any product of P's is scrambling. The next theorem gives sufficient condition for a strong version of C3 under the assumption that the set $\mathcal{P}$ has the following "closedness" property.

C. If $P_1, P_2 \in \mathcal{P}$ then, for any $1 \leq i \leq N$, the matrix obtained from P_1 by replacing the ith row of P_1 by the ith row of P_2 belongs to $\mathcal{P}$.

THEOREM 2. *Suppose that the set* $\mathcal{P}$ *has property* C. *Further, assume that each* $P \in \mathcal{P}$ *has a single ergodic class and that there is an integer* s *with* $1 \leq s \leq N$ *such that, for each* $P \in \mathcal{P}$, $p_{ss} > 0$ *and* s *is an ergodic state of* P. *Then there is an integer* μ *with* $1 \leq \mu \leq N-1$ *such that for all* $k \geq \mu$ *and any* $P_i \in \mathcal{P}(1 \leq i \leq k)$ *the* sth *column of the matrix* $P_k \ldots P_1$ *has only positive entries.*

PROOF. Let $S(0) = \{s\}$. Define the sets $R(k-1)$ and $S(k)$ for $k \geq 1$ by

$$R(k-1) = \bigcup_{j=0}^{k-1} S(j) \text{ and } S(k) = \{i \mid i \notin R(k-1), \sum_{j \in R(k-1)} p_{ij} > 0 \quad \text{for all } P \in \mathcal{P}\}.$$

From this definition it follows that there is a first integer μ with $1 \leq \mu \leq N-1$ such that $R(\mu) = \{1,\ldots,N\}$ when we can prove that $S(k) \neq \phi$ when $R(k-1) \neq \{1,\ldots,N\}$. To do this , assume to the contrary that there is an integer $k \geq 1$ such that $S(k) = \phi$ and $R(k-1) \neq \{1,\ldots,N\}$. Then, for each $i \notin R(k-1)$, we can find a matrix $P^{(i)} \in \mathcal{P}$ such that $p_{ij}^{(i)} = 0$ for all $j \in R(k-1)$. Now, by property C, there is a matrix $P^* \in \mathcal{P}$ whose ith row is equal to the ith row of $P^{(i)}$ for all $i \notin R(k-1)$. Then, $p^*_{ij} = 0$ for all $i \notin R(k-1)$ and $j \in R(k-1)$. However, this is a contradiction since $s \in R(k-1)$ and it is assumed that P^* has a single ergodic class and that s is ergodic under P^*. This proves the existence of the above integer μ. Now, choose $k \geq \mu$, $P_i \in \mathcal{P}(1 \leq i \leq k)$ and $j \neq s$. By the construction of the sets S(h), we have $(P_k \ldots P_{k-m+1})_{js} > 0$ for some m with $1 \leq m \leq \mu$. Now since $p_{ss} > 0$ for all P, we get $(P_k \ldots P_1)_{is} > 0$ for all i which proves the desired result.

REFERENCES

[1] BROWN, B.W., On the Iterative Method of Dynamic Programming on a Finite Space Discrete Time Markov Process, *Ann. Math. Statist.*, Vol. 36 (1965), 1279-1285.

[2] DOOB, J.L., *Stochastic Processes*, Wiley, New York, 1953.

[3] HAJNAL, J., Weak Ergodicity in Nonhomogeneous Markov-chains, *Proc. Cambridge Philos. Soc.*, Vol. 54 (1958), 233-246.

[4] PAZ, A. & REICHAW, M., Ergodic Theorems for Sequences of Infinite Stochastic Matrices, *Proc. Cambridge Philos. Soc.*, Vol. 63 (1967), 777-784.

[5] PAZ, A., *Introduction to Probabilistic Automata*, Academic Press, New York, 1971.

[6] SENETA, E., *Non-negative Matrices*, George Allen & Unwin Ltd., London, 1973.

[7] WOLFOWITZ, J., Products of Indecomposable, Aperiodic, Stochastic Matrices, *Proc. Amer. Math. Soc.*, Vol. 14 (1963), 733-737.