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Eventually cyclic matrices and a test for strong eventual nonnegativity

Abstract
Eventually r-cyclic matrices are defined, and it is shown that if A is an eventually r-cyclic matrix A having rank A^2 = rank A, then A is r-cyclic with the same cyclic structure. This result and known Perron-Frobenius theory of eventually nonnegative matrices are used to establish an algorithm to determine whether a matrix is strongly eventually nonnegative (i.e., is an eventually nonnegative matrix having a power that is both irreducible and nonnegative).

Keywords
Eventually nonnegative matrix, Eventually r-cyclic matrix, Strongly eventually nonnegative matrix, Perron-Frobenius

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EVENTUALLY CYCLIC MATRICES AND A TEST FOR STRONG EVENTUAL NONNEGATIVITY∗

LESLIE HOGBEN†

Abstract. Eventually \( r \)-cyclic matrices are defined, and it is shown that if \( A \) is an eventually \( r \)-cyclic matrix \( A \) having rank \( A^2 = \text{rank} A \), then \( A \) is \( r \)-cyclic with the same cyclic structure. This result and known Perron-Frobenius theory of eventually nonnegative matrices are used to establish an algorithm to determine whether a matrix is strongly eventually nonnegative (i.e., is an eventually nonnegative matrix having a power that is both irreducible and nonnegative).

Key words. Eventually nonnegative matrix, Eventually \( r \)-cyclic matrix, Strongly eventually nonnegative matrix, Perron-Frobenius.

AMS subject classifications. 15B48, 05C50, 15A18.

1. Introduction. A matrix \( A \in \mathbb{R}^{n \times n} \) is eventually nonnegative (respectively, eventually positive) if there exists a positive integer \( k_0 \) such that for all \( k \geq k_0 \), \( A^k \geq 0 \) (respectively, \( A^k > 0 \)), and the least such \( k_0 \) is called the power index of \( A \). A matrix \( A \in \mathbb{R}^{n \times n} \) is strongly eventually nonnegative if \( A \) is eventually nonnegative and there is a positive integer \( k \) such that \( A^k \geq 0 \) and \( A^k \) is irreducible [4].

For a fixed \( n \), the power index of an eventually positive or eventually nonnegative \( n \times n \) matrix may be arbitrarily large, so it is not possible to show a matrix is not eventually positive or eventually nonnegative by computing powers. Eventual positivity is characterized by Perron-Frobenius properties, which provide necessary and sufficient conditions to determine whether a matrix is eventually positive. Unfortunately, nilpotent matrices, which have no Perron-Frobenius structure, are eventually nonnegative, and there is no known “if and only if” test using Perron-Frobenius-type properties for eventual nonnegativity. Strongly eventually nonnegative matrices are a subset of the eventually nonnegative matrices having weaker connections with Perron-Frobenius theory than eventually positive matrices, but still allowing an “if and only if” test, presented here in Algorithm 3.1, which provides a way to show a matrix is not strongly eventually nonnegative. The proof of the algorithm is based on results from the literature and the result that if \( \text{rank} A^2 = \text{rank} A \) and \( A \) is eventually \( r \)-cyclic, then \( A \) is \( r \)-cyclic (Corollary 2.8 below).

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Throughout this paper all matrices are real. An eigenvalue $\lambda$ of $A$ is a dominant
eigenvalue if $|\lambda| = \rho(A)$ (where $\rho(A)$ denotes the spectral radius). A matrix is even-
tually positive if and only if $\rho(A)$ is a simple eigenvalue having positive right and left
eigenvectors and $A$ has no other dominant eigenvalue [6].

Just as digraphs are central to the Perron-Frobenius theory of nonnegative ma-
trices, they are central to our analysis of strongly eventually nonnegative matrices,
and we need additional notation and terminology. A digraph $\Gamma = (V, E)$ consists of a
finite, nonempty set $V$ of vertices, together with a set $E \subseteq V \times V$ of arcs. Note that
a digraph allows loops (arcs of the form $(v, v)$) and may have both arcs $(v, w)$ and
$(w, v)$ but not multiple copies of the same arc.

Let $A = [a_{ij}] \in \mathbb{R}^{n \times n}$. The digraph of $A$, denoted $\Gamma(A)$, has vertex set $\{1, \ldots, n\}$
and arc set $\{(i, j) : a_{ij} \neq 0\}$. If $R, C \subseteq \{1, 2, \ldots, n\}$, then $A[R|C]$ denotes the subma-
trix of $A$ whose rows and columns are indexed by $R$ and $C$, respectively. If $C = R$, then
$A[R|R]$ can be abbreviated to $A[R]$. For a digraph $\Gamma = (V, E)$ and $W \subseteq V$, the induced
subdigraph $\Gamma[W]$ is the digraph with vertex set $W$ and arc set $\{(v, w) \in E : v, w \in W\}$.
For a square matrix $A$, $\Gamma(A[W])$ is identified with $\Gamma(A)[W]$ by a slight abuse of no-
tation.

A square matrix $A$ is reducible if there exists a permutation matrix $P$ such that

$$
PAP^T = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix},
$$

where $A_{11}$ and $A_{22}$ are nonempty square matrices and $0$ is a (possibly rectangular)
block consisting entirely of zero entries, or $A$ is the $1 \times 1$ zero matrix. If $A$ is not reducible, then $A$ is called irreducible. A digraph $\Gamma$ is strongly connected (or strong)
if for any two distinct vertices $v$ and $w$ of $\Gamma$, there is a walk in $\Gamma$ from $v$ to $w$. It
is well known that for $n \geq 2$, $A$ is irreducible if and only if $\Gamma(A)$ is strong. For a
strong digraph $\Gamma$, the index of imprimitivity is the greatest common divisor of the
the lengths of the closed walks in $\Gamma$. A strong digraph is primitive if its index of
imprimitivity is one; otherwise it is imprimitive. The strong components of $\Gamma$ are the
maximal strongly connected subdigraphs of $\Gamma$.

For $r \geq 2$, a digraph $\Gamma = (V, E)$ is cyclically $r$-partite if there exists an ordered
partition $(V_1, \ldots, V_r)$ of $V$ into $r$ nonempty sets such that for each arc $(i, j) \in E$, there
exists $t \in \{1, \ldots, r\}$ with $i \in V_t$ and $j \in V_{t+1}$ (where we adopt the convention that
index $r + 1$ is interpreted as 1). For $r \geq 2$, a strong digraph $\Gamma$ is cyclically $r$-partite
if and only if $r$ divides the index of imprimitivity (see, for example, [2, p. 70]). For
$r \geq 2$, a matrix $A \in \mathbb{R}^{n \times n}$ is called $r$-cyclic if $\Gamma(A)$ is cyclically $r$-partite. If $\Gamma(A)$ is
cyclically $r$-partite with ordered partition $\Pi$, then we say $A$ is $r$-cyclic with partition
$\Pi$, or $\Pi$ describes the $r$-cyclic structure of $A$. The ordered partition $\Pi = (V_1, \ldots, V_r)$
is consecutive if $V_1 = \{1, \ldots, i_1\}, V_2 = \{i_1 + 1, \ldots, i_2\}, \ldots, V_r = \{i_{r-1} + 1, \ldots, n\}$. If
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A is r-cyclic with consecutive ordered partition Π, then A has the block form

\[
\begin{bmatrix}
0 & A_{12} & 0 & \cdots & 0 \\
0 & 0 & A_{23} & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & A_{r-1,r} \\
A_{r1} & 0 & 0 & \cdots & 0
\end{bmatrix},
\]

where \(A_{i,i+1} = A[V_i|V_{i+1}].\) For any r-cyclic matrix A, there exists a permutation matrix \(P\) such that \(PAP^T\) is r-cyclic with consecutive ordered partition. The cyclic index of \(A\) is the largest \(r\) for which \(A\) is r-cyclic.

An irreducible nonnegative matrix \(B\) is primitive if \(\Gamma(B)\) is primitive, and the index of imprimitivity of \(B\) is the index of imprimitivity of \(\Gamma(B)\). It is well known that a nonnegative matrix is primitive if and only if it is eventually positive. Let \(B \geq 0\) be irreducible with index of imprimitivity \(r \geq 2\). Then \(r\) is the cyclic index of \(B\), \(\Gamma(B)\) is cyclically r-partite with ordered partition \(\Pi = (V_1, \ldots, V_r)\), and the sets \(V_i\) are uniquely determined (up to cyclic permutation of the \(V_i\)) (see, for example, [2, p. 70]). Furthermore, \(\Gamma(B^r)\) is the disjoint union of \(r\) primitive digraphs on the sets of vertices \(V_i, i = 1, \ldots, r\) (see, for example, [8, Fact 29.7.3]).

Section 2 presents the definition of eventually r-cyclic matrices and some of their properties, including that if \(\text{rank } A^2 = \text{rank } A\) and \(A\) is eventually r-cyclic, then \(A\) is r-cyclic. It is also shown there that a strongly eventually nonnegative matrix is eventually r-cyclic or eventually positive. These results are used in Section 3 to establish the validity of Algorithm 3.1, which tests whether a matrix is strongly eventually nonnegative; examples illustrating the use of the algorithm are included.

2. Eventually r-cyclic matrices.

**Definition 2.1.** For an ordered partition \(\Pi = (V_1, \ldots, V_r)\) of \(\{1, \ldots, n\}\) into \(r\) nonempty sets, the cyclic characteristic matrix \(C_\Pi = [c_{ij}]\) of \(\Pi\) is the \(n \times n\) matrix such that \(c_{ij} = 1\) if there exists \(\ell \in \{1, \ldots, r\}\) such that \(i \in V_\ell\) and \(j \in V_{\ell+1}\), and \(c_{ij} = 0\) otherwise.

Note that for any ordered partition \(\Pi = (V_1, \ldots, V_r)\) of \(\{1, \ldots, n\}\) into \(r\) nonempty sets, \(C_\Pi\) is r-cyclic, and \(\Gamma(C_\Pi)\) contains every arc \((v, w)\) for \(v \in V_\ell\) and \(w \in V_{\ell+1}\).

**Definition 2.2.** For matrices \(A = [a_{ij}], C = [c_{ij}] \in \mathbb{R}^{n \times n}\), matrix \(A\) is conformal with \(C\) if for all \(i, j = 1, \ldots, n\), \(c_{ij} = 0\) implies \(a_{ij} = 0\). Equivalently, \(A\) is conformal with \(C\) if \(\Gamma(A)\) is a subdigraph of \(\Gamma(C)\) (with the same set of vertices).

Let \(\Pi\) be an ordered partition into \(r\) nonempty sets. Then \(A\) is r-cyclic with partition \(\Pi\) if and only if \(A\) is conformal with \(C_\Pi\).
Observation 2.3. If $A, B, C, D \in \mathbb{R}^{n \times n}$, $C, D \geq 0$, $A$ is conformal with $C$ and $B$ is conformal with $D$, then $AB$ is conformal with $CD$. If $A$ is an $r$-cyclic matrix with partition $\Pi$, then $A^k$ is conformal with $C^k$.

Observation 2.4. Let $B \geq 0$ be irreducible with index of imprimitivity $r \geq 2$ and let $\Pi$ describe the $r$-cyclic structure of $B$. Then for $d$ large enough, $C_\Pi$ is conformal with $B^{dr+1}$, i.e., $\Gamma(B^{dr+1}) = \Gamma(C_\Pi)$.

Definition 2.5. A matrix $A$ is eventually $r$-cyclic if there exists an ordered partition $\Pi$ of $\{1, \ldots, n\}$ into $r \geq 2$ nonempty sets, and a positive integer $m$ such that for all $k \geq m$, $A^k$ is conformal with $C^k$. In this case, we say that $\Pi$ describes the eventually $r$-cyclic structure of $A$. The eventually cyclic index of $A$ is the largest $r$ for which $A$ is eventually $r$-cyclic.

Many eventual properties, such as eventual positivity or eventual nonnegativity, can be established by establishing the property for two consecutive powers of a matrix. The following proposition shows this is sufficient for eventually $r$-cyclic matrices.

Proposition 2.6. If $A$ is a matrix and for some nonnegative integer $d$, $A^{dr+1}$ is $r$-cyclic with partition $\Pi$ and $A^{dr}$ is conformal with $C^k$, then $A$ is eventually $r$-cyclic and $\Pi$ describes the eventually $r$-cyclic structure of $A$.

Proof. For every positive integer $k$ sufficiently large, there exist $a, b \geq 0$ such that $k = a(dr) + b(dr + 1)$ (see e.g., [2, Lemma 3.5.5]). Fix $k = a(dr) + b(dr + 1)$. Then $A^k = A^{a(dr) + b(dr + 1)} = (A^{dr})^a(A^{dr+1})^b$ is conformal with $(C_\Pi)^aC^k$, which is conformal with $C^{ad}_\Pi C^b_\Pi = C^{k}_\Pi$. $\square$

For any square matrix $A$, rank $A^2 = \text{rank } A$ if and only if the degree of 0 as a root of the minimal polynomial of $A$ is at most 1. The combinatorial structure of eventually nonnegative matrices with this property was studied in [3], where it is shown that if $A$ is an irreducible eventually nonnegative matrix such that $\text{rank } A^2 = \text{rank } A$, then some power of $A$ is irreducible and nonnegative, i.e., $A$ is strongly eventually nonnegative. A matrix with the property that rank $A^2 = \text{rank } A$ behaves very nicely in regard to being eventually $r$-cyclic, because this property eliminates issues caused by a nonzero nilpotent part. The following notation will be used in the next proof. The nullspace of a (possibly rectangular) $p \times q$ matrix $M$ is $\text{NS}(M) = \{v \in \mathbb{R}^q : Mv = 0\}$, and the left nullspace of $M$ is $\text{LNS}(M) = \{w \in \mathbb{R}^p : w^TM = 0\}$.

Theorem 2.7. If $A \in \mathbb{R}^{n \times n}$, rank $A^2 = \text{rank } A$, and there is a positive integer $m$ divisible by $r$ such that $A^{m+1}$ is $r$-cyclic with partition $\Pi$ and $A^m$ is conformal with $C^k$, then $A$ is $r$-cyclic with partition $\Pi$.

Proof. Assume that $A$, $m$, $r$ and $\Pi = (V_1, \ldots, V_r)$ satisfy the hypotheses. Since rank $A^2 = \text{rank } A$, for every positive integer $k$, rank $A^k = \text{rank } A$. Thus, NS($A^k$) =
Initially, we assume that $\Pi$ is consecutive. Partition $A = [A_{ij}]$ where $A_{ij} = A[V_i | V_j]$. By hypothesis, $A^m = B_1 \oplus \cdots \oplus B_r$ is a block diagonal matrix, and thus

\[
\begin{aligned}
NS(A^m) &= \{[v_1^T, \ldots, v_r^T]^T : v_\ell \in NS(B_\ell), \ell = 1, \ldots, r\}, \\
LNS(A^m) &= \{[w_1^T, \ldots, w_r^T]^T : w_\ell \in LNS(B_\ell), \ell = 1, \ldots, r\}.
\end{aligned}
\]

For $v_\ell \in NS(B_\ell)$, define $\hat{v_\ell} = [0^T, \ldots, 0^T, v_\ell^T, 0^T, \ldots, 0^T]^T$, so $A^m \hat{v_\ell} = 0$. Since $NS(A) = NS(A^m)$,

\[
0 = A \hat{v_\ell} = \begin{bmatrix}
A_{1\ell} v_\ell \\
\vdots \\
A_{r\ell} v_\ell
\end{bmatrix},
\]

and so $A_{i\ell} v_\ell = 0, i = 1, \ldots, r$. Similarly, $w_\ell^T A_{\ell j} = 0^T, j = 1, \ldots, r$ for $w_\ell \in LNS(B_\ell)$. That is, for all $i, j = 1, \ldots, r$,

\[
NS(B_\ell) \subseteq NS(A_{i\ell}) \quad \text{and} \quad LNS(B_\ell) \subseteq LNS(A_{\ell j}). \tag{2.1}
\]

Now consider

\[
A^{m+1} = A^m A = \begin{bmatrix}
B_1 A_{11} & B_1 A_{12} & \cdots & B_1 A_{1r} \\
B_2 A_{21} & B_2 A_{22} & \cdots & B_2 A_{2r} \\
\vdots & \vdots & \ddots & \vdots \\
B_r A_{r1} & B_r A_{r2} & \cdots & B_r A_{rr}
\end{bmatrix}.
\]

Since $A^{m+1}$ is conformal with $C_\Pi$,

\[
B_\ell A_{\ell j} = 0 \quad \text{unless} \quad j \equiv \ell + 1 \mod r.
\]

Since $B_\ell v = 0$ implies $A_{i\ell} v = 0, i = 1, \ldots, r$,

\[
A_{i\ell} A_{\ell j} = 0 \quad \text{unless} \quad j \equiv \ell + 1 \mod r. \tag{2.2}
\]

By considering $A^{m+1} = AA^m$ and the left null space,

\[
A_{i\ell} A_{\ell j} = 0 \quad \text{unless} \quad i \equiv \ell - 1 \mod r. \tag{2.3}
\]

So the only product of the form $A_{i\ell} A_{\ell j}$ that is not required to be 0 is $A_{\ell-1,\ell} A_{\ell,\ell+1}$ (with indices mod $r$). Thus,

\[
B_\ell = (A_{\ell,\ell+1} \cdots A_{r1} A_{12} \cdots A_{\ell-1,\ell})^{m/r},
\]

so $NS(A_{\ell-1,\ell}) \subseteq NS(B_\ell)$ and $LNS(A_{\ell,\ell+1}) \subseteq LNS(B_\ell)$. Then by (2.1),

\[
NS(A_{\ell-1,\ell}) = NS(B_\ell) \quad \text{and} \quad LNS(A_{\ell,\ell+1}) = LNS(B_\ell). \tag{2.4}
\]
So by (2.1), \( \text{NS}(A_{\ell-1,\ell}) \subseteq \text{NS}(A_{i,\ell}) \) for \( i = 1, \ldots, r \). This implies that for each \( i \) there exists a (possibly rectangular) matrix \( M_i \) such that

\[
A_{i,\ell} = M_iA_{\ell-1,\ell}.
\] (2.5)

So for \( i \not\equiv \ell - 1 \mod r \),

\[
0 = \text{rank}(A_{i\ell}A_{\ell,\ell+1}) \text{ by (2.3)} \geq \text{rank}(M_iA_{\ell-1,\ell}A_{\ell,\ell+1}) - \text{rank}(A_{\ell-1,\ell}) \text{ by [9, (2.7)]} = \text{rank}(A_{i\ell}) \text{ by (2.5)}.
\]

Thus, \( A_{i\ell} = 0 \) for \( i \not\equiv \ell - 1 \mod r \), and \( A \) is \( r \)-cyclic with partition \( \Pi \).

Without the assumption that \( \Pi \) is consecutive, there exists a permutation matrix \( P \) such that \( (PAP^T)_{m+1} = PA_{m+1}P^T \) is \( r \)-cyclic with consecutive partition \( \Pi' \) and \( (PAP^T)^m = PA^mP^T \) is conformal with \( C_{\Pi'} \). Since \( \text{rank}(PAP^T)^2 = \text{rank}(PAP^T) \), \( (PAP^T)_{ij} = 0 \) unless \( j \equiv i + 1 \mod r \) (using the block structure of \( C_{\Pi'} \)). Thus, \( A \) is \( r \)-cyclic with partition \( \Pi' \). \( \Box \)

**Corollary 2.8.** Let \( A \in \mathbb{R}^{n \times n} \) have \( \text{rank}A^2 = \text{rank}A \). Then \( A \) is eventually \( r \)-cyclic if and only if \( A \) is \( r \)-cyclic.

We now return to strongly eventually nonnegative matrices. We need a preliminary lemma.

**Lemma 2.9.** If \( A \) and \( B \) are \( n \times n \) nonnegative matrices having all diagonal entries positive, then \( \Gamma(A) \cup \Gamma(B) \subseteq \Gamma(AB) \).

**Proof.** Let \( A = [a_{ij}] \) and \( B = [b_{ij}] \). If \((u, v) \in \Gamma(A)\), then

\[
(AB)_{uv} = \sum_{i=1}^{n} a_{ui}b_{iv} \geq a_{uv}b_{uv} > 0,
\]

so \((u, v) \in \Gamma(AB)\). Thus, \( \Gamma(A) \subseteq \Gamma(AB) \). The case \( \Gamma(B) \subseteq \Gamma(AB) \) is similar. \( \Box \)

**Remark 2.10.** Let \( A \) be a strongly eventually nonnegative matrix with power index \( k_0 \) and \( r \) dominant eigenvalues. Since \( A \) is eventually nonnegative, \( \rho(A) \) is an eigenvalue of \( A \) [5]. There is a positive integer \( k \) such that \( A^k \geq 0 \) and \( A^k \) is irreducible. For any such \( k \), \( A^k \) has positive left and right eigenvectors for its spectral radius; the same is true for every power of \( A \), including \( A \) itself. If \( r = 1 \), then \( A \) is eventually positive [6]. Now assume \( \ell \geq k_0 \) such that \( \rho(A^\ell) \) is simple. Then \( A^\ell \) is irreducible [1, Corollary 2.3.15], and so the \( r \) dominant eigenvalues of \( A^\ell \) are \( \{\rho(A^\ell), \rho(A^\ell)\omega, \ldots, \rho(A^\ell)\omega^{r-1}\} \) where \( \omega \) is a primitive \( r \)th root of unity [1, Theorem
2.2.20]. Furthermore, \( A^\ell \) is \( r \)-cyclic [1, Theorem 2.2.20]. Note that \( \ell \geq k_0 \) with \( \rho(A^\ell) \)

simple necessarily exists (e.g., \( \ell = kk_0r + 1 \)). If \( u \geq k_0 \) and \( \rho(A^u) \)

is simple, then any positive integers \( x, y \) divisible by \( r \), the multiplicity of \( \rho(A^{x+uy}) = \rho(A^x)^u\rho(A^y)^u \) is \( r \), so \( \Gamma(A^{x+uy}) \) has \( r \) strong components [1, Theorem 2.3.14].

**Theorem 2.11.** Let \( A \) be strongly eventually nonnegative matrix \( A \) having \( r \geq 2 \)

dominant eigenvalues and power index \( k_0 \). Then there exists a positive integer \( m \geq k_0 \)

divisible by \( r \) such that \( A^{m+1} \) is \( r \)-cyclic with partition \( \Pi \) and \( A^m \) is conformal with \( C_r^r \).

**Proof.** Choose a positive integer \( \ell \geq k_0 \) such that \( \rho(A^\ell) \) is simple, so \( A^\ell \)

is irreducible and \( r \)-cyclic, and let \( \Pi = (V_1, \ldots, V_r) \) denote an ordered partition that

describes the \( r \)-cyclic structure of \( A^\ell \). Let \( m = \ell r \); the spectral radius of \( A^{m+1} \geq 0 \)

is simple, and thus \( A^{m+1} \) is irreducible and \( r \)-cyclic. Let \( \Psi = (W_1, \ldots, W_r) \) be an

ordered partition that describes the \( r \)-cyclic structure of \( A^{m+1} \). It suffices to show that

\( A^m \) is conformal with \( C_r^m \). Note that for an \( r \)-cyclic matrix, in any power that

is a multiple of \( r \), the order of the sets in the partition is irrelevant, since all arcs are

within partition sets. Thus, it suffices to show that the unordered sets \( \{V_1, \ldots, V_r\} \)

and \( \{W_1, \ldots, W_r\} \) are equal.

By Observation 2.4, we can choose \( s \) large enough so that the diagonal blocks

\( A^{frs}[V_i] \) and \( A^{(m+1)rs}[V_i] \) are positive for \( i = 1, \ldots, r \). Since \( A^{frs}A^{(m+1)rs} = A^{frs+(m+1)rs} \), \( \Gamma(A^{frs}A^{(m+1)rs}) \) has \( r \) strong components. Since all diagonal entries of \( \Gamma(A^{frs}) \) and \( \Gamma(A^{(m+1)rs}) \) are positive, by Lemma 2.9,

\[ \Gamma(A^{frs}) \cup \Gamma(A^{(m+1)rs}) \subseteq \Gamma(A^{frs}A^{(m+1)rs}). \]

But \( \Gamma(A^{frs}) \cup \Gamma(A^{(m+1)rs}) \) contains the complete digraphs on \( V_i, i = 1, \ldots, r \) and

\( W_i, i = 1, \ldots, r \), so the only way for \( \Gamma(A^{frs}A^{(m+1)rs}) \) to have \( r \) strong components is to have \( \{V_1, \ldots, V_r\} = \{W_1, \ldots, W_r\} \).

**Corollary 2.12.** If \( A \in \mathbb{R}^{n \times n} \) is strongly eventually nonnegative with \( r \geq 2 \)

dominant eigenvalues, then \( A \) is eventually \( r \)-cyclic.

**Corollary 2.13.** If \( A \in \mathbb{R}^{n \times n} \) is strongly eventually nonnegative with \( r \geq 2 \)

dominant eigenvalues and rank \( A^2 = \text{rank} A \), then \( A \) is \( r \)-cyclic.

### 3. Testing for strong eventual nonnegativity

In this section, we provide an algorithm to test whether a matrix is strongly eventually nonnegative and prove that it works, illustrate the algorithm with examples, and discuss computational issues related to the algorithm.
3.1. Algorithm and proof.

**Algorithm 3.1.** Test a matrix for strong eventual nonnegativity.

Let $A$ be an $n \times n$ real matrix.

1. Compute the spectrum $\sigma(A)$, set $r$ equal to the number of dominant eigenvalues, and set $\omega = e^{2\pi i/r}$.

2. If the multiset of dominant eigenvalues is not $\{\rho(A), \rho(A)\omega, \ldots, \rho(A)\omega^{r-1}\}$, then $A$ is not strongly eventually nonnegative, else continue.

3. Compute eigenvectors $v$ and $w$ for $\rho(A)$ for $A$ and $A^T$.

4. If $v$ or $w$ is not a multiple of a positive eigenvector, then $A$ is not strongly eventually nonnegative, else continue.

5. If $r = 1$, then $A$ is eventually positive (and thus is strongly eventually nonnegative), else continue.

6. Compute a nonsingular matrix $S \in \mathbb{R}^{n \times n}$ such that

$$A = S (\text{diag}(\rho(A), \rho(A)\omega, \ldots, \rho(A)\omega^{r-1}) \oplus M) S^{-1}.$$

7. Set $B_1 = S (\text{diag}(1, \omega, \ldots, \omega^{r-1}) \oplus 0) S^{-1}$.

8. If $B_1$ is not nonnegative or $B_1$ is not $r$-cyclic, then $A$ is not strongly eventually nonnegative, else continue.

9. Set $q = \lceil \frac{n}{r} \rceil r$. Then $A$ is strongly eventually nonnegative if and only if $A^q$ and $A^{q+1}$ are conformal with $B_1^r$ and $B_1$, respectively.

The following result will be used in the proof of Algorithm 3.1.

**Theorem 3.2.** [4] If $A$ is strongly eventually nonnegative and has $r$ dominant eigenvalues, then the dominant eigenvalues of $A$ are $\{\rho(A), \rho(A)\omega, \ldots, \rho(A)\omega^{r-1}\}$ where $\omega = e^{2\pi i/r}$.

**Theorem 3.3.** Algorithm 3.1 is correct.

**Proof.** The first three assertions that $A$ is or is not strongly eventually nonnegative are justified by the following theorems:

2. Theorem 3.2.

4. Remark 2.10.

5. Remark 2.10.

There are two remaining assertions, in Steps 8 and 9. Define $B = \frac{1}{\rho(A)} A$, and note that $B$ has one of the following properties if and only if $A$ has the same property: nonnegative, $r$-cyclic, strongly eventually nonnegative, conformal with a matrix $C$. 
Thus, we establish the results for $B$ rather than $A$. There exists a nonsingular $T \in \mathbb{R}^{(n-r)\times(n-r)}$ such that $M = T(G \oplus N)T^{-1}$ where $N$ is nilpotent and $G$ is nonsingular. Define $B_0 = S(0 \oplus T(G \oplus 0)T^{-1})S^{-1}$. From the definitions of $B_1$ and $B_0$,

\[ B_1^{dr+1} = B_1 \text{ for } d \geq 0, \quad \rho(B_1) = 1, \quad \rho(B_0) < 1, \]

\[ B^k = B_1^k + B_0^k \text{ for } k \geq n, \quad \text{and } \text{rank}(B_1 + B_0)^2 = \text{rank}(B_1 + B_0). \]

Thus, $\lim_{k \to \infty} B_0^k = 0$, and

\[ \lim_{d \to \infty} B_1^{dr+1} = B_1. \tag{3.1} \]

Thus, if $B_1$ has an negative entry or is not $r$-cyclic, $B_1^{dr+1}$ retains this property for arbitrarily large $d$ and so $B$ and thus $A$ are not eventually nonnegative. This establishes the validity of Step 8.

For Step 9, we may assume that $B_1 \geq 0$ is $r$-cyclic with partition $\Pi$. By (3.1), for $k$ large enough, $(B_1^k)_{ij} > 0$ implies $(B^k)_{ij} > 0$. By the construction of $B_1$ from $S$, $B_1$ and $B_1^T$ have positive eigenvectors for simple eigenvalue 1, so by [1, Corollary 2.3.15], $B_1$ is irreducible. Then by Observation 2.4 and the fact that $B_1^{dr+1} = B_1$, $C_\Pi$ is conformal with $B_1$.

First assume $B^q$ and $B^{q+1}$ are conformal with $B_1^r$ and $B_1$, respectively. By Proposition 2.6, $B$ is eventually $r$-cyclic and $\Pi$ describes the eventually $r$-cyclic structure of $B$. So for $k$ large enough, (3.1) implies $B^k \geq 0$ and if $\gcd(r,k) = 1$, then $\rho(B^k)$ is simple so $B^k$ is irreducible. Thus, $B$ is strongly eventually nonnegative.

For the converse, assume that $B$ is strongly eventually nonnegative, so $B_1 + B_0$ is strongly eventually nonnegative. By Theorem 2.11, there exists a positive integer $m \geq k_0$ divisible by $r$ such that $(B_1 + B_0)^m = B_1^{m} + B_0^{m}$ is conformal with $C_\Pi^r$. Since $\text{rank}(B_1 + B_0)^2 = \text{rank}(B_1 + B_0)$, by Theorem 2.7, $B_1 + B_0$ is conformal with $C_\Pi$. As a consequence of (3.1), $B_1$ must be $r$-cyclic with the same partition $\Pi$. Since $B_1 \geq 0$ and $C_\Pi$ is conformal with $B_1$, a matrix is conformal with $C_\Pi^k$ if and only if it is conformal with $B_1^k$. Thus, $(B_1 + B_0)^q$ and $(B_1 + B_0)^{q+1}$ are conformal with $B_1^{r}$ and $B_1$, respectively. Since $q \geq n$, $B^q = (B_1 + B_0)^q$ and $B^{q+1} = (B_1 + B_0)^{q+1}$. \[

3.2. \text{ Examples.}\] We illustrate the algorithm with examples.

\textbf{Example 3.4.} Let

\[
A = \begin{bmatrix}
0 & 2 & 0 & 0 & 2 & 0 \\
0 & 0 & 0 & 2 & 0 & 2 \\
0 & 2 & 0 & 0 & 2 & 0 \\
2 & 1 & 2 & 0 & -1 & 0 \\
0 & 0 & 0 & 2 & 0 & 2 \\
2 & -1 & 2 & 0 & 1 & 0
\end{bmatrix},
\]

EVENTUALLY CYCLIC MATRICES AND A TEST FOR STRONG EVENTUAL NONNEGATIVITY
Step 1: $\sigma(A) = \{4, -2 + 2i\sqrt{3}, -2 - 2i\sqrt{3}, 0, 0, 0\}$, so $r = 3$ and $\rho(A) = 4$. The eigenvectors of $A$ and $A^T$ for eigenvalue $\rho(A) = 4$ are both $[1, 1, 1, 1, 1, 1, 1]^T$. For Steps 6 and 7, a possible $S$ and the resulting $B_1$ are

$$S = \begin{bmatrix}
1 & (-1-i\sqrt{3}) & 0 & 0 & -1 \\
1 & (-1+i\sqrt{3}) & 0 & -\frac{1}{2} & 0 \\
1 & (-1-i\sqrt{3}) & 0 & 0 & 1 \\
1 & 1 & -1 & 0 & 0 \\
1 & (-1+i\sqrt{3}) & 0 & \frac{1}{2} & 0 \\
1 & 1 & 1 & 0 & 0
\end{bmatrix},
B_1 = \begin{bmatrix}
0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 \\
0 & 0 & 0 & \frac{1}{2} & 0 & \frac{1}{2} \\
0 & \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 \\
0 & 0 & \frac{1}{2} & 0 & 0 & 0 \\
\frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 & 0 \\
\frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 & 0
\end{bmatrix}.$$}

Clearly, $B_1 \geq 0$. By examining $\Gamma(B_1)$ we see that $B_1$ is 3-cyclic with partition $\{(1, 3), (2, 5), (4, 6)\}$. Computations then verify that $A^6$ and $A^7$ are conform with $B_1^6$ and $B_1^7$, respectively, so $B$ is strongly eventually nonnegative.

**Example 3.5.** Let

$$A = \begin{bmatrix}
\frac{1}{4} & -\frac{3}{4} & -\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 \\
-\frac{1}{4} & \frac{3}{4} & -\frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & 0 & 0 \\
0 & 0 & 1 & -1 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} & 0 & 0 \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & -\frac{1}{4} \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & -\frac{1}{4}
\end{bmatrix}.$$}

Step 1: $\sigma(A) = \{2, -2, -1, -1, 1, 0, 0\}$, so $r = 2$ and $\rho(A) = 2$. The eigenvectors of $A$ and $A^T$ for eigenvalue $\rho(A) = 2$ are both $[1, 1, 1, 1, 1, 1, 1]^T$. For Steps 6 and 7, a possible $S$ and the resulting $B_1$ are

$$S = \begin{bmatrix}
1 & -1 & -1 & 8 & 0 & 0 & 0 & -4 \\
1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & -1 & 0 & -8 & 0 & 0 & 0 & 0 \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 2 \\
1 & 1 & 0 & 0 & -1 & -2 & -1 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 2 & 0 & 0 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix},
B_1 = \begin{bmatrix}
0 & 0 & 0 & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
0 & 0 & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
0 & 0 & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
0 & 0 & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\
\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4}
\end{bmatrix},$$

and $B_1$ is clearly nonnegative and 2-cyclic. Step 9: Computations show $A^6$ is not conformal with $B_1$, so $A$ is not strongly eventually nonnegative.
Example 3.6. Let

\[ A = \begin{bmatrix} 0 & 0 & 45 & 1155 \\ 0 & 0 & 2097 & -897 \\ 871 & 329 & 0 & 0 \\ 187 & 1013 & 0 & 0 \end{bmatrix} . \]

Step 1: \( \sigma(A) = \{1200, -1200, 684i\sqrt{3}, -684i\sqrt{3}\} \), so \( r = 2 \) and \( \rho(A) = 1200 \). The eigenvectors of \( A \) and \( A^T \) for eigenvalue \( \rho(A) = 1200 \) are \([1, 1, 1, 1]^T \) and \([7, 5, 9, 3]^T \), respectively. For Steps 6 and 7, a possible \( S \) and the resulting \( B_1 \) are

\[ S = \begin{bmatrix} 1 & -1 & -\frac{5i}{3\sqrt{3}} & \frac{5i}{3\sqrt{3}} \\ 1 & -1 & \frac{7i}{3\sqrt{3}} & -\frac{7i}{3\sqrt{3}} \\ 1 & 1 & -\frac{1}{3} & -\frac{1}{3} \\ 1 & 1 & 1 & 1 \end{bmatrix} , \quad B_1 = \begin{bmatrix} 0 & 0 & \frac{3}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ 0 & 0 & \frac{3}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{7}{\sqrt{3}} & \frac{5}{\sqrt{3}} & 0 & 0 \\ \frac{7}{\sqrt{3}} & \frac{5}{\sqrt{3}} & 0 & 0 \end{bmatrix} , \]

so \( B_1 \geq 0 \) and 2-cyclic. Since \( A \) is conformal with \( B_1 \), \( A^4 \) and \( A^5 \) are conformal with \( B_1^4 \) and \( B_1 \), respectively, and \( A \) is strongly eventually nonnegative.

In this particular case (because the spectrum consists entirely of real multiples of roots of unity), we can extend the spectral analysis in the algorithm to estimate the power index of \( A \). Set \( B = \frac{1}{1200} A \) and \( \alpha = \rho(B - B_1) \), and define

\[ \hat{B}_0 = \frac{1}{\alpha}(B - B_1) = \begin{bmatrix} 0 & 0 & -\frac{5}{3\sqrt{3}} & -\frac{5}{3\sqrt{3}} \\ 0 & 0 & \frac{4\sqrt{3}}{3} & -\frac{4\sqrt{3}}{3} \\ \frac{1}{3\sqrt{3}} & -\frac{1}{3\sqrt{3}} & 0 & 0 \\ -\frac{1}{3\sqrt{3}} & \frac{1}{3\sqrt{3}} & 0 & 0 \end{bmatrix} . \]

Since \( \sigma(\hat{B}_0) = \{i, -i, 0, 0\} \), \( \hat{B}_0^{4k+1} = \hat{B}_0 \). Solving \( \alpha^k|\hat{B}_0| = (B_1)^{24} \) yields \( k = 109.001 \), and in fact \( A^{109} \geq 0 \), but \( A \) is nonnegative thereafter.

3.3. Computational issues. The computations in Examples 3.4, 3.5 and 3.6 were all done in exact arithmetic, so there was no issue of roundoff error. However, eigenvalues will generally need to be computed as decimal approximations, and roundoff error is an issue. Fortunately, to implement Algorithm 3.1 it is not necessary to compute Jordan forms (or eigenvectors for repeated eigenvalues), which are difficult to do in decimal arithmetic. If the matrix \( A \) is eventually nonnegative, then the dominant eigenvalues are simple and well spread out. The accuracy of the computations will depend on the condition number of each dominant eigenvalue, which in turn depends on the angle between the eigenvectors of \( A \) and \( A^T \) (see, for example, [7, p. 323]). Step 6 of Algorithm 3.1 requires computing a matrix \( S = [s_1, \ldots, s_n] \) such that

\[ S^{-1}AS = \text{diag}(\rho(A), \rho(A)\omega, \ldots, \rho(A)\omega^{r-1}) \oplus M. \]
This can be done as follows:

- Compute eigenvectors $s_1, \ldots, s_r$ for the dominant eigenvalues $\rho(A), \rho(A)\omega, \ldots, \rho(A)\omega^{r-1}$.
- Extend $\{s_1, \ldots, s_r\}$ to a basis $\{s_1, \ldots, s_r, u_{r+1}, \ldots, u_n\}$ for $\mathbb{R}^n$.
- Set $U = [s_1, \ldots, s_r, u_{r+1}, \ldots, u_n]$. Then
  \[ U^{-1}AU = \begin{bmatrix} H_{11} & H_{12} \\ 0 & H_{22} \end{bmatrix} \text{ where } H_{11} = \text{diag}(\rho(A), \rho(A)\omega, \ldots, \rho(A)\omega^{r-1}). \]
- Since $\sigma(H_{11})\cap\sigma(H_{22}) = \emptyset$, by [7, Lemma 7.1.5], we can solve a system of linear equations to find a matrix $Z \in \mathbb{R}^{r \times (n-r)}$ such that $H_{11}Z - ZH_{22} = -H_{12}$.
- Then for $Y = \begin{bmatrix} I_r & Z \\ 0 & I_{n-r} \end{bmatrix}$, $Y^{-1}U^{-1}AU = \begin{bmatrix} H_{11} & 0 \\ 0 & H_{22} \end{bmatrix}$, and $S = UY$ is a satisfactory matrix for Step 6.

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