Minimum Rank of Graphs with Loops

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Abstract
A loop graph $S$ is a finite undirected graph that allows loops but does not allow multiple edges. The set $S(S)$ of real symmetric matrices associated with a loop graph of order $n$ is the set of symmetric matrices $A = [a(ij)]$ is an element of $\mathbb{R}^{n \times n}$ such that $a(ij)$ not equal 0 if and only if $ij$ is an element of $E(S)$. The minimum (maximum) rank of a loop graph is the minimum (maximum) of the ranks of the matrices in $S(S)$. Loop graphs having minimum rank at most two are characterized (by forbidden induced subgraphs and graph complements) and loop graphs having minimum rank equal to the order of the graph are characterized. A Schur complement reduction technique is used to determine the minimum ranks of cycles with various loop configurations; the minimum ranks of complete graphs and paths with various configurations of loops are also determined. Unlike simple graphs, loop graphs can have maximum rank less than the order of the graph. Some results are presented on maximum rank and which ranks between minimum and maximum can be realized. Interesting open questions remain.

Keywords
loop graph, minimum rank, maximum nullity, zero forcing number, spanning composite cycle, generalized cycle, Schur complement, matrix, graph

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MINIMUM RANK OF GRAPHS WITH LOOPS*

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Abstract. A loop graph \( G \) is a finite undirected graph that allows loops but does not allow multiple edges. The set \( S(G) \) of real symmetric matrices associated with a loop graph \( G \) of order \( n \) is the set of symmetric matrices \( A = [a_{ij}] \in \mathbb{R}^{n \times n} \) such that \( a_{ij} \neq 0 \) if and only if \( ij \in E(G) \). The minimum (maximum) rank of a loop graph is the minimum (maximum) of the ranks of the matrices in \( S(G) \). Loop graphs having minimum rank at most two are characterized (by forbidden induced subgraphs and graph complements) and loop graphs having minimum rank equal to the order of the graph are characterized. A Schur complement reduction technique is used to determine the minimum ranks of cycles with various loop configurations; the minimum ranks of complete graphs and paths with various configurations of loops are also determined. Unlike simple graphs, loop graphs can have maximum rank less than the order of the graph. Some results are presented on maximum rank and which ranks between minimum and maximum can be realized. Interesting open questions remain.

Key words. Loop graph, Minimum rank, Maximum nullity, Zero forcing number, Spanning composite cycle, Generalized cycle, Schur complement, Matrix, Graph.

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1. Introduction. A simple graph does not allow loops or multiple edges, whereas a loop graph allows (but does not require) loops. The set of edges of a simple graph describes the nonzero pattern of the off-diagonal entries of the graph’s family of real symmetric matrices (with no constraints on diagonal entries), whereas the edges of a loop graph completely describe the nonzero pattern of the graph’s family of real symmetric matrices. Note that a loop graph that does not contain any loops requires matrices to have a zero diagonal, whereas a simple graph (which by definition has no loops) does not require a zero diagonal. To avoid confusion, we use \( G \) etc. to denote a simple graph and \( \mathcal{G} \) etc. to denote a loop graph. Formal definitions and other terminology can be found in Section 11.

The minimum rank problem for a simple or loop graph is to determine the mini-
minimum of the ranks among the matrices in the family described by the simple or loop graph. The minimum rank problem for simple graphs has been studied extensively (see [14] and the references therein). Some work has been done on loop graphs, including complete determination of minimum rank for loop trees [12], cut-vertex reduction [25], and characterizations of extreme minimum rank for loop graphs that do not have loops [16]. However, far fewer results have been obtained about the minimum rank problem for loop graphs than for simple graphs.

Characterizations of loop graphs having minimum rank at most two (by forbidden induced subgraphs and graph complements) are established in Section 2; the proof makes use of the analogous characterizations for simple graphs [5], but the forbidden subgraphs are substantially different. In Section 3 the characterization of minimum rank equal to order if and only if there is a unique spanning composite cycle is extended from loopless loop graphs (zero diagonal minimum rank) [16] to every loop graph. Section 4 presents a technique for reducing the minimum rank problem for a specific graph to a smaller one through the use of the Schur complement. This method is applied to cycles in Section 5 which contains characterizations of the minimum ranks of complete graphs, paths, and cycles with various configurations of loops. Unlike simple graphs, loop graphs can have maximum rank less than the order of the graph [16]. Thus, it is of interest to determine the maximum rank and which ranks between minimum and maximum can be realized; these topics are discussed in Section 6. Section 7 presents examples showing that certain results, including the Graph Complement Conjecture and Colin de Verdière type parameters do not extend to loop graphs, and asks questions for future research.

1.1. Notation and terminology. For a loop graph \( \mathcal{G} = (V(\mathcal{G}), E(\mathcal{G})) \), the finite nonempty set of vertices is denoted by \( V(\mathcal{G}) \) and the set of edges \( E(\mathcal{G}) \) is a set of two element multisets of vertices (i.e., the two vertices in an edge need not be distinct). A loop is an edge with two copies of one vertex. The edge \( \{u, v\} \) is often denoted by \( uv \) (or in the case of a loop \( \{u, u\} \) by \( uu \)). A simple graph \( G = (V(G), E(G)) \) is defined analogously, except an edge is a two element set of vertices (i.e., the two vertices in an edge must be distinct).

For a symmetric \( n \times n \) real matrix \( A \), the loop graph of \( A \) is \( \mathcal{G}(A) = (V, E) \), where \( V = \{1, \ldots, n\} \) and \( E = \{uv \mid a_{uv} \neq 0\} \), and the simple graph of \( A \) is \( \mathcal{G}(A) = (V, E) \), where \( V = \{1, \ldots, n\} \) and \( E = \{uv \mid u \neq v \text{ and } a_{uv} \neq 0\} \). Let \( \mathcal{G} = (V, E) \) be a loop graph of order \( n \) (normally \( V = \{1, \ldots, n\} \); otherwise we associate \( V \) with \( \{1, \ldots, n\} \)). The set of real symmetric matrices described by \( \mathcal{G} \) is

\[
S(\mathcal{G}) = \{A \in \mathbb{R}^{n \times n} : A^T = A \text{ and } \mathcal{G}(A) = \mathcal{G}\}.
\]

The definition for a simple graph \( G \) is analogous using \( \mathcal{G}(A) \), rather than \( \mathcal{G}(A) \), with the effect that the diagonal entries of \( A \) are completely free for \( A \in S(G) \). The
adjacency matrix $A_{\mathcal{G}}$ is in $\mathcal{S}(\mathcal{G})$ and analogously for a simple graph. The minimum rank and the maximum nullity of a loop graph $\mathcal{G}$ are

$$\text{mr}(\mathcal{G}) = \min\{\text{rank } A | A \in \mathcal{S}(\mathcal{G})\} \quad \text{and} \quad M(\mathcal{G}) = \max\{\text{null } A | A \in \mathcal{S}(\mathcal{G})\}.$$ 

The definitions of minimum rank and maximum nullity for a simple graph $G$ are analogous, but the set of matrices is now $\mathcal{S}(G)$, so the minimum or maximum is taken over symmetric matrices whose off-diagonal pattern of nonzero entries is described by the edges of $G$. Clearly $\text{mr}(\mathcal{G}) + M(\mathcal{G}) = |\mathcal{G}|$.

A path in a simple or loop graph is a subgraph with distinct vertices $v_1, v_2, \ldots, v_t$ and edge set $\{v_1v_2, v_2v_3, \ldots, v_{t-1}v_t\}$. A cycle in a simple or loop graph is a subgraph with distinct vertices $v_1, v_2, \ldots, v_t$, where $t \geq 3$ and edge set $\{v_1v_2, v_2v_3, \ldots, v_{t-1}v_t, v_1v_t\}$; a $k$-cycle is a cycle with $k$ vertices. By definition, the complete graph on $n$ vertices, $\mathcal{K}_n$, has all loops, and the complete bipartite graph on $s$ and $t$ vertices, $\mathcal{K}_{s,t}$, has no loops. For any loop graph $\mathcal{G}$, $\mathcal{G}^0$ denotes the loop graph having the same underlying simple graph as $\mathcal{G}$ but no loops, and $\mathcal{G}^\ell$ has the same underlying simple graph as $\mathcal{G}$ but all loops.

The subgraph $\mathcal{G}[W]$ of $\mathcal{G} = (V, E)$ induced by $W \subseteq V$ is the subgraph with vertex set $W$ and edge set $\{wu | wu \in E \text{ and } w, u \in W\}$. The complement of $\mathcal{G}$ is the loop graph $\overline{\mathcal{G}} = (V, \overline{E})$, where $\overline{E} = E(\mathcal{K}_n) \setminus E$. The union of loop graphs $\mathcal{G}_i = (V_i, E_i)$ is $\bigcup_{i=1}^h \mathcal{G}_i = (\bigcup_{i=1}^h V_i, \bigcup_{i=1}^h E_i)$; if the $V_i$ are pairwise disjoint, then the union can be denoted by $\bigcup_{i=1}^h \mathcal{G}_i$. Let $\mathcal{G} = (V, E)$ be a loop graph of order $n$. If $\mathcal{G}_1$ and $\mathcal{G}_2$ are disjoint loop graphs, the join $\mathcal{G}_1 \vee \mathcal{G}_2$ of $\mathcal{G}_1$ and $\mathcal{G}_2$ is the graph with vertex set $V(\mathcal{G}_1 \vee \mathcal{G}_2) = V(\mathcal{G}_1) \cup V(\mathcal{G}_2)$ and edge set $E(\mathcal{G}_1 \vee \mathcal{G}_2) = E(\mathcal{G}_1) \cup E(\mathcal{G}_2) \cup E$, where $E$ consists of all the edges $uv$ with $u \in V(\mathcal{G}_1)$ and $v \in V(\mathcal{G}_2)$.

Vertex $u$ is a neighbor of vertex $v$ in $\mathcal{G}$ if and only if $uv \in E$ (so $u$ is a neighbor of itself if and only if it has a loop). The set of neighbors of $v$ is denoted by $N_\mathcal{G}(v)$ (or $N(v)$ if $\mathcal{G}$ is clear). The degree of vertex $v$ in $\mathcal{G}$ is $\deg_\mathcal{G} v = |N_\mathcal{G}(v)|$ (and $\deg_\mathcal{G} v$ can be denoted by $\deg v$ if $\mathcal{G}$ is clear). The minimum degree of $\mathcal{G} = (V, E)$ is $\delta(\mathcal{G}) = \min\{\deg v | v \in V\}$.

Let $A$ be an $n \times n$ matrix. For $\alpha, \beta \subseteq \{1, 2, \ldots, n\}$, the submatrix of $A$ lying in rows indexed by $\alpha$ and columns indexed by $\beta$ is denoted by $A[\alpha, \beta]$: $A[\alpha, \beta]_{\alpha, \beta}$ is also denoted by $A[\alpha]$ and is a principal submatrix. We also define $A[\alpha, \alpha] := A[\alpha, \alpha]_{\alpha, \alpha}$, $A[\alpha, \alpha] := A[\alpha, \alpha]_{\alpha, \alpha}$, and $A(\alpha) := A[\alpha, \alpha]$, where $\alpha = \{1, 2, \ldots, n\} \setminus \alpha$.

1.2. Composite cycles and the characteristic polynomial. A composite cycle $C$ of a loop graph $\mathcal{G}$ is a subgraph of $\mathcal{G}$, where each connected component is one of the following: A cycle, an edge (meaning an edge and its two distinct endpoints), or a loop (meaning a vertex $v$ and its edge $vv$). An edge can be thought of as a 2-cycle.
and a loop as a 1-cycle, but they behave differently when evaluating determinants, so we define a “cycle” to have at least 3 vertices. Composite cycles are also called *generalized cycles* and [1, 2]-*factors*. The order of $C$ is the number of vertices in $C$. A composite cycle of order $|G|$ is said to be a spanning composite cycle (or a perfect [1, 2]-factor). The following notation is adapted from [10] (although there the term “generalized cycle” is used). Given a composite cycle $C$, define $nc(C)$ to be the number of distinct cycles in $C$, and $ne(C)$ to be the number of even components of $C$, that is, the number of edges plus the number of cycles of even order. The set of all composite cycles of order $k$ of a loop graph $G$ is denoted by $cyc_k(G)$. With a composite cycle $C$, we associate a permutation of the vertices of $C$ as follows. For each cycle in $C$, fix an orientation and then associate a directed graph cycle $(v_1, v_2, \ldots, v_k)$ with the cyclic permutation $(v_1 v_2 \cdots v_k)$. Each edge component $v_1 v_2$ of $C$ is associated with the 2-cycle permutation $(v_1 v_2)$ and each loop $v_1 v_1$ is associated with the 1-cycle permutation $(v_1)$, which fixes $v_1$. The permutation $\pi_C$ is defined to be the product of these associated permutation cycles. Note that there are $2^{nc(C)}$ different choices for the orientation of the cycles of $C$, and each choice yields a permutation that has the same sign as $\pi_C$, namely $(-1)^{ne(C)}$. The sum of all $k \times k$ principal minors of an $n \times n$ matrix $A = (a_{ij}) \in S(\mathcal{G})$ is denoted $S_k(A)$, and can be expressed using composite cycles [21] as

$$S_k(A) = \sum_{C \in cyc_k(\mathcal{G}(A))} (-1)^{ne(C)} 2^{nc(C)} a_{i_1 \pi_C(i_1)} \cdots a_{i_k \pi_C(i_k)}, \quad (1.1)$$

where $\{i_1, i_2, \ldots, i_k\}$ is the vertex set of $C$ and the sum over the empty set is defined to be zero. The characteristic polynomial $p_A(x)$ of $A$ is

$$x^n - S_1(A)x^{n-1} + S_2(A)x^{n-2} + \cdots + (-1)^{n-1} S_{n-1}(A)x + (-1)^n S_n(A).$$

Note that for $A \in S(\mathcal{G})$, det $A = S_n(A)$ can be computed using spanning composite cycles, and if $\mathcal{G}$ has a unique spanning composite cycle then det $A \neq 0$. The next remark extends and generalizes Remark 1.4 in [10].

**Remark 1.1.** For a real symmetric matrix $A$ with $p_A(x) = x^n + c_1 x^{n-1} + \cdots + c_k x^{n-k} + \cdots + c_n$, rank $A = \max \{|k| \mid c_k \neq 0\}$. Let $\mathcal{G}$ be a loop graph of order $n$. If $\mathcal{G}$ has no composite cycle of order $k$, then rank $A \neq k$ for all $A \in S(\mathcal{G})$. If $\mathcal{G}$ has no composite cycle of order $k$ for all $k > m$, then rank $A \leq m$ for all $A \in S(\mathcal{G})$, and hence mr($\mathcal{G}$) $\leq m$.

**1.3. Additional results.** This section contains some obvious extensions to loop graphs of well-known results for minimum rank of simple graphs, and summarizes additional known results for loop graphs that we will use.
Observation 1.2. Let $\mathcal{G}$ be a loop graph.

1. If $\mathcal{G}$ is obtained from the simple graph $G$ by adding some configuration of loops to $G$, then $\text{mr}(G) \leq \text{mr}(\mathcal{G})$.
2. If $H$ is an induced subgraph of $\mathcal{G}$, then $\text{mr}(H) \leq \text{mr}(\mathcal{G})$.
3. $\mathcal{G}$ has no edges if and only if $\text{mr}(\mathcal{G}) = 0$.
4. If the connected components of $\mathcal{G}$ are $\mathcal{G}_1, \mathcal{G}_2, \ldots, \mathcal{G}_t$, then $\text{mr}(\mathcal{G}) = \sum_{i=1}^{t} \text{mr}(\mathcal{G}_i)$.

A loop graph $\mathcal{T}$ is a forest if $\mathcal{T}$ does not have any cycles, and a tree is a connected forest. Note that a forest is permitted to have loops. The technique in the next remark is known for matrices described by simple graphs (see, for example, [10]), and the same inductive reasoning applies to loop graphs.

Remark 1.3. Suppose $A \in \mathcal{S}(\mathcal{G})$ and $\mathcal{T}$ is a loopless forest that is a subgraph of $\mathcal{G}$. If $\mathcal{G}$ has a loop at vertex $v$, then the $v,v$-entry of $B := \frac{1}{w} A$ is one. There exists a nonsingular diagonal matrix $D$ such that $(DBD)_{uv} = 1$ for every $uv \in E(\mathcal{T})$ and $(DBD)_{vv} = 1$ ($v$ is chosen as the root). Observe that for $D$ nonsingular diagonal, $B \in \mathcal{S}(\mathcal{G})$ implies $DBD \in \mathcal{S}(\mathcal{G})$ and $\text{rank}(DBD) = \text{rank} B$, so when showing that a matrix in $\mathcal{S}(\mathcal{G})$ realizing a specific rank does not exist, without loss of generality we can assume the entries associated with the edges of a loopless forest are all one, and one nonzero diagonal entry can be assumed to be one (if such exists).

The zero forcing number was introduced in [2] for simple graphs and extended to loop graphs in [22]. Let $\mathcal{G} = (V,E)$ be a loop graph, with each vertex colored either white or blue. If exactly one neighbor $v$ of $u$ is white, then change the color of $v$ to blue (the possibility that $u = v$ is permitted); this is the color-change rule for loop graphs. When the color-change rule is applied to $u$ changing the color of $v$, we say $u$ forces $v$, and write $u \rightarrow v$. Given an initial coloring of $\mathcal{G}$, the final coloring is the result of applying the color-change rule until no more changes are possible. A zero forcing set for $\mathcal{G}$ is a subset of vertices $B$ such that if initially the vertices in $B$ are colored blue and the remaining vertices are colored white, then all the vertices of $\mathcal{G}$ are blue in the final coloring. The zero forcing number $Z(\mathcal{G})$ is the minimum cardinality of a zero forcing set $B \subseteq V$.

Theorem 1.4. [22] For every loop graph $\mathcal{G}$, $M(\mathcal{G}) \leq Z(\mathcal{G})$. If $\mathcal{T}$ is a forest, then $M(\mathcal{T}) = Z(\mathcal{T})$. 

2. Low minimum rank. In this section, we characterize loop graphs having minimum rank at most two. Minimum rank at most three was characterized for loop graphs that have no loops in [16], where it was shown that:

• \( \text{mr}(G^0) = 0 \) if and only if \( G^0 \) has no edges.
• \( \text{mr}(G^0) \neq 1 \).
• For \( G^0 \) connected, \( \text{mr}(G^0) = 2 \) if and only if \( G^0 = \overline{K_{n_1,n_2}} \) with \( n_1, n_2 \geq 1 \).
• For \( G^0 \) connected, \( \text{mr}(G^0) = 3 \) if and only if \( G^0 = \overline{K_{n_1,n_2,\ldots,n_t}} \) with \( t \geq 3 \) and \( n_i \geq 1 \) for \( i = 1, \ldots, t \).

Observation 2.1. A loop graph \( \mathcal{G} \) has \( \text{mr}(\mathcal{G}) = 0 \) if and only if \( \mathcal{G} = \overline{K_n} \), and \( \text{mr}(\mathcal{G}) = 1 \) if and only if \( \mathcal{G} = \overline{K_s} \cup \overline{K_r} \) with \( s \geq 1 \) and \( r \geq 0 \).

We extend Barrett, van der Holst, and Loewy’s characterizations of simple graphs having minimum rank at most two to loop graphs, but with a different set of forbidden induced subgraphs, the set \( \mathcal{F}_{\text{mr}},2 \) shown in Figure 2.1 (see Theorem 2.3 below).

![Figure 2.1](https://example.com/figure2_1.png)

**Fig. 2.1.** The set \( \mathcal{F}_{\text{mr}},2 = \{\mathcal{F}_1, \ldots, \mathcal{F}_{10}\} \) of forbidden induced subgraphs for minimum rank at most two.

Following the definitions of \( \mathcal{F} \)-free and \( \mathcal{F} \)-free for simple graphs in [5], we say a loop graph \( \mathcal{G} \) is \( \mathcal{F} \)-free if \( \mathcal{G} \) does not contain \( \mathcal{F} \) as an induced subgraph, and for a set \( \mathcal{F} \) of loop graphs, \( \mathcal{G} \) is \( \mathcal{F} \)-free if \( \mathcal{G} \) is \( \mathcal{F} \)-free for all \( \mathcal{F} \in \mathcal{F} \). The next theorem, due to Barrett, van der Holst, and Loewy, will be used:
Minimum Rank of Graphs With Loops

**Theorem 2.2.** [5, Theorem 6] Let $G$ be a simple graph. The following are equivalent:

1. $\text{mr}(G) \leq 2$.
2. $G$ is $\{P_4, \text{dart, } K_{3,3,3}, P_3 \cup K_2, 3K_2\}$-free.
3. $\overline{\mathcal{G}} = (K_{s_1} \cup K_{s_2} \cup K_{p_1,q_1} \cup \cdots \cup K_{p_k,q_k}) \cup K_r$ for some nonnegative $s_1, s_2, k, p_i, q_i, r$ with $p_i + q_i \geq 1$ for $i = 1, \ldots, k$.

The next theorem characterizes loop graphs having minimum rank at most two.

**Theorem 2.3.** Let $\mathcal{G}$ be a loop graph. The following are equivalent:

1. $\text{mr}(\mathcal{G}) \leq 2$.
2. $\mathcal{G}$ is $\mathcal{F}_{\text{mr2}}$-free for the set $\mathcal{F}_{\text{mr2}}$ of loop graphs shown in Figure 5.4.
3. $\overline{\mathcal{G}} = (\mathcal{R}_{s_1} \cup \mathcal{R}_{s_2} \cup \mathcal{R}_{p_1,q_1} \cup \cdots \cup \mathcal{R}_{p_k,q_k}) \cup \mathcal{R}_r$ for some nonnegative $s_1, s_2, k, p_i, q_i$ with $p_i + q_i \geq 1$ for $i = 1, \ldots, k$.
4. $\mathcal{G} = (\mathcal{R}_{s_1} \cup (\mathcal{R}_{p_1} \cup \mathcal{R}_{q_1}) \cup \cdots \cup (\mathcal{R}_{p_k} \cup \mathcal{R}_{q_k})) \cup \overline{\mathcal{R}}_r$ for some nonnegative $s_1, s_2, k, p_i, q_i, r$ with $p_i + q_i \geq 1$ for $i = 1, \ldots, k$.

**Proof.** We modify conditions (3) and (4) by removing the isolated vertices from the latter:

$$\overline{\mathcal{G}} = \mathcal{R}_{s_1} \cup \mathcal{R}_{s_2} \cup \mathcal{R}_{p_1,q_1} \cup \cdots \cup \mathcal{R}_{p_k,q_k}$$

(2.1)

for some nonnegative $s_1, s_2, k, p_i, q_i$ with $p_i + q_i \geq 1$ for $i = 1, \ldots, k$ and $k \geq 1$ or $s_1, s_2 \geq 1$, and

$$\mathcal{G} = \mathcal{R}_{s_1} \cup (\mathcal{R}_{p_1} \cup \mathcal{R}_{q_1}) \cup \cdots \cup (\mathcal{R}_{p_k} \cup \mathcal{R}_{q_k})$$

(2.2)

for some nonnegative $s_1, s_2, k, p_i, q_i$ with $p_i + q_i \geq 1$ for $i = 1, \ldots, k$ and $k \geq 1$ or $s_1, s_2 \geq 1$. We prove that conditions (1), (2), (2.1), and (2.2) are equivalent for loop graphs with positive minimum degree. The result then follows, since taking a disjoint union of $\mathcal{G}$ and $\overline{\mathcal{R}}_r$ is equivalent to bordering a matrix $M \in \mathcal{S}(\mathcal{G})$ with blocks of zeros. So, henceforth we assume $\delta(\mathcal{G}) \geq 1$.

1. $\Rightarrow$ 2. Every graph in $\mathcal{F}_{\text{mr2}}$ has minimum rank greater than two. So, if $\mathcal{G}$ contains some $\mathcal{G}_i \in \mathcal{F}_{\text{mr2}}$ as an induced subgraph, then $\text{mr}(\mathcal{G}) \geq 3$.

2. $\Rightarrow$ (2.1) Assume $\mathcal{G}$ is $\mathcal{F}_{\text{mr2}}$-free. It is easy to check that any loop configuration of any of the six graphs $P_4$, dart, $\kappa$, $K_{3,3,3}$, $P_3 \cup K_2$, and $3K_2$ contains at least one induced subgraph in $\mathcal{F}_{\text{mr2}}$ (see Appendix 7 for details). Thus, the associated simple graph $G$ of $\mathcal{G}$ is $\{P_4, \text{dart, } K_{3,3,3}, P_3 \cup K_2, 3K_2\}$-free, and so by Theorem 2.2

$$\overline{G} = (K_{s_1} \cup K_{s_2} \cup K_{p_1,q_1} \cup \cdots \cup K_{p_k,q_k}) \cup K_r$$

for some nonnegative $s_1, s_2, k, p_i, q_i, r$ with $p_i + q_i \geq 1$ for $i = 1, \ldots, k$.

Hence, $G$ is of the form $(K_{s_1,s_2} \cup (K_{p_1} \cup K_{q_1}) \cup \cdots \cup (K_{p_k} \cup K_{q_k})) \cup \overline{K_r}$ and $\mathcal{G}$ is $G$ with a certain loop configuration. We show that without loss of generality we may
assume \( r = 0 \). Since \( \delta(\mathbb{S}) \geq 1 \), every vertex in \( \overline{K_r} \) must have a loop. Suppose first that the simple graph of \( \mathbb{S} \) is \( G = \overline{K_r} \). Since \( \mathbb{S} \) is \( \overline{\mathbb{S}}_1 \)-free, \( r \leq 2 \), and so \( \mathbb{S} = \mathbb{S}_1 \cup \mathbb{S}_1 \) or \( \mathbb{S} = \mathbb{S}_1 \), both of which have the required form. Now suppose that \( \mathbb{S} = \mathbb{S}_1 \cup (\overline{K_r})^\ell \) with \( |\mathbb{S}| \geq 1 \) and \( r \geq 1 \). Since \( \mathbb{S} \) is \( \{\overline{\mathbb{S}}_2, \overline{\mathbb{S}}_3\} \)-free, every non-loop edge of \( \mathbb{S}_1 \) must have loops on both of its endpoints. Since \( \delta(\mathbb{S}) \geq 1 \) and \( \mathbb{S} \) is \( \overline{\mathbb{S}}_1 \)-free, \( \mathbb{S}_1 \) can have at most one connected component and \( r = 1 \). If \( \mathbb{S} \neq \mathbb{S}_1 \), then there would be some pair of vertices \( v \) and \( u \) such that \( \mathbb{S}_1 \) does not contain the edge \( uv \), in which case \( \mathbb{S} \) would contain \( \overline{\mathbb{S}}_1 \). So \( \mathbb{S}_1 = \mathbb{S}_1 \), and \( \mathbb{S} = \mathbb{S}_1 \cup \mathbb{S}_1 \), which has the required form. Since the cases with \( r \geq 1 \) all have the required form, we now assume \( r = 0 \).

Thus, we assume \( \mathbb{S} \) has the form \( K_{s_1, s_2} \lor (K_{p_1} \cup K_{q_1}) \lor \cdots \lor (K_{p_k} \cup K_{q_k}) \) with some loop configuration, so the complement of \( \mathbb{S} \) is \( K_{s_1} \cup K_{s_2} \cup K_{p_1, q_1} \cup \cdots \cup K_{p_k, q_k} \) with the complementary loop configuration. A loop graph is \( F_{mr^2} \)-free if and only if its complement is \( H_{mr^2} \)-free for the set \( H_{mr^2} \) shown in Figure 2.2.

![Fig. 2.2](image)

**Fig. 2.2.** The set \( H_{mr^2} = \{S_1, \ldots, S_{10}\} \) of complements of forbidden induced subgraphs for minimum rank \( \leq 2 \), where \( S_i \) is the complement of \( \overline{S}_i \) in Figure 2.1.

Consider a matrix \( M \in S(\overline{\mathbb{S}}) \), which has the form

\[
M = \begin{bmatrix}
A_1 & A_2 & \cdots & A_k \\
B_1 & B_2 & \cdots & B_k
\end{bmatrix},
\]

where \( A_i \in S(K_{s_i}) \), \( B_i \in S(K_{p_i, q_i}) \), and all other entries are zero. We now want to consider the diagonals of these block matrices of type \( A_i \), representing a complete
simple graph, and type $B$, representing a complete bipartite simple graph, given that $G$ does not contain any of the subgraphs $H_1, \ldots, H_{10}$ of Figure 2.2. With the allowed forms of block matrices, we show $M \in S(K_{s_1} \cup K_{s_2} \cup K_{p_1,q_1} \cup \cdots \cup K_{p_k,q_k})$ for appropriate $s_i, p_i, q_i, k$.

A matrix of type $A$ represents a complete simple graph, so all off-diagonal entries are nonzero. If there are three loopless vertices in the complete graph, the graph contains $H_1$. So the zero-nonzero pattern of a matrix of type $A$ have one of the three following forms $A_\alpha$, $\alpha \in \{a, b, c\}$:

$$A_a = \begin{bmatrix} * & \cdots & * \\ \vdots & \ddots & \vdots \\ * & \cdots & * \end{bmatrix}, \quad A_b = \begin{bmatrix} 0 & * & \cdots & * \\ * & \ddots & \cdots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ * & \cdots & \cdots & * \end{bmatrix}, \quad A_c = \begin{bmatrix} 0 & * & \cdots & * \\ * & 0 & \cdots & * \\ \vdots & \ddots & \ddots & \vdots \\ * & \cdots & \cdots & * \end{bmatrix}. $$

Let $s_\alpha$ denote the dimension of the matrix $A_\alpha$ for $\alpha \in \{a, b, c\}$. Notice that the graphs corresponding to $A_b$ and $A_c$ already contain a $K_2$ with one loop if $s_b \geq 2$ and $s_c \geq 3$. If we take the disjoint union one of these graphs with any other graph, the union will contain $H_5$ or $H_6$. Therefore $B$ must have one of the following six forms:

$$B_a = \begin{bmatrix} * & \cdots & * \\ \vdots & \ddots & \vdots \\ * & \cdots & * \end{bmatrix}, \quad B_b = \begin{bmatrix} * & \cdots & * \\ \vdots & \ddots & \vdots \\ * & \cdots & * \end{bmatrix}, \quad B_c = \begin{bmatrix} * & \cdots & * \\ \vdots & \ddots & \vdots \\ * & \cdots & * \end{bmatrix}. $$
Let \( p_\beta \) and \( q_\beta \) be the number of vertices in the two partitions for \( \beta \in \{a, b, c, d, e, f\} \). Notice that if we allow either \( p_\beta \) or \( q_\beta \) to be zero, the corresponding matrix represents a union with isolated vertices (with or without loops). Since we handle this case separately, here we assume \( p_\beta \geq 1 \) and \( q_\beta \geq 1 \). If the matrices other than \( B_a \) are too big, we show that the corresponding bipartite graphs have an induced \( \mathcal{H}_2 \) or \( \mathcal{H}_3 \), and so are prohibited:

If \( p_b \geq 2 \), then \( \mathcal{G}(B_b) \) contains \( \mathcal{H}_3 \) (since we assume \( q_b \geq 1 \)). For \( p_b = 1, q_b \geq 1 \), \( \mathcal{G}(B_b) \) contains a \( K_2 \) with one loop. Thus, in this case we cannot have a union with other graphs because the union would contain \( \mathcal{H}_5 \) or \( \mathcal{H}_6 \), so \( M = B_b \). But \( \mathcal{G}(B_b) = \mathcal{H}_1 \vee \mathcal{H}_n \), so \( \delta(\mathcal{H}) = 0 \) and this case is excluded.

By construction of \( B_c, p_c \geq 2 \), so \( \mathcal{G}(B_c) \) contains \( \mathcal{H}_2 \) (since we assume \( q_c \geq 1 \)), and this case is excluded.

If \( p_d \geq 2 \) and \( q_d \geq 2 \), \( \mathcal{G}(B_d) \) contains \( \mathcal{H}_3 \), so without loss of generality \( p_d = 1 \). If \( q_d \geq 2 \) the corresponding graph contains a \( K_2 \) with one loop and can therefore not be in a union with another graph, and as for \( B_b \) this case is excluded. So \( B_d \) can only appear with \( p_d = 1, q_d = 1 \), and \( \mathcal{G}(B_d) = \mathcal{H}_2 \).

By construction of \( B_e, p_e \geq 2 \). For \( q_e \geq 2, \mathcal{G}(B_e) \) contains \( \mathcal{H}_2 \). So \( B_e \) can only appear with \( p_e \geq 2 \) and \( q_e = 1 \). But then \( \mathcal{G}(B_e) \) contains an induced \( \mathcal{P}_3 \). So if we have a union of \( \mathcal{G}(B_e) \) with another graph, the union contains \( \mathcal{H}_4 \) or \( \mathcal{H}_9 \). Thus, \( M = B_e \) and \( \mathcal{G}(B_e) = (\mathcal{H}_1 \cup \mathcal{H}_1 \cup \mathcal{H}_1 \cup \cdots \cup \mathcal{H}_1) \vee \mathcal{H}_1 \), so \( \delta(\mathcal{H}) = 0 \) and this case is excluded.

\[
B_c = \begin{bmatrix}
* & * & \cdots & * \\
* & * & \cdots & * \\
\vdots & \vdots & \ddots & \vdots \\
* & \cdots & * & *
\end{bmatrix}, \quad B_d = \begin{bmatrix}
* & * & \cdots & * \\
* & * & \cdots & * \\
\vdots & \vdots & \ddots & \vdots \\
* & \cdots & * & *
\end{bmatrix}
\]

\[
B_e = \begin{bmatrix}
* & * & \cdots & * \\
* & * & \cdots & * \\
\vdots & \vdots & \ddots & \vdots \\
* & \cdots & * & *
\end{bmatrix}, \quad B_f = \begin{bmatrix}
* & * & \cdots & * \\
* & * & \cdots & * \\
\vdots & \vdots & \ddots & \vdots \\
* & \cdots & * & *
\end{bmatrix}
\]
Also notice that $\mathfrak{G}(B_f)$ already contains $\mathfrak{G}_1$, so $B_f$ does not appear.

Thus, the types of $B$ matrices that can occur are $B_a$ for any size, $B_d$ for $p_d = 1$, $q_d = 1$ (so $\mathfrak{G}(B_d) = \mathfrak{G}_2$), or matrices that represent isolated vertices, with a total of at most two loops.

We can consider $B_d$ with $p_d = 1$, $q_d = 1$, and an isolated vertex with a loop, as being type $A_a$. Isolated vertices without loops can be viewed as type $B_a$ with $q_a = 0$ (which we now allow). Thus, all permissible forms of $M$ can be constructed using only blocks of type $A_a$ and $B_a$. If we take a block diagonal matrix that includes nonzero diagonal entries in three distinct blocks, the graph contains an induced $\mathfrak{G}_4$. Therefore we can only combine blocks such that at most two of the $A_a$ blocks appear. To summarize, we can combine up to two matrices of type $A_a$ with an arbitrary number of matrices of type $B_a$. Hence, $\mathfrak{G}(M)$ has the required form (2.1).

(2.1) $\iff$ (2.2) is immediate and (2.2) $\Rightarrow$ (1) follows from the proof of [5, Theorem 2], because the construction of a matrix $C \in S(K_{s_1,s_2} \lor (K_{p_1} \cup K_{q_1}) \lor \cdots \lor (K_{p_k} \cup K_{q_k}))$ with rank $C \leq 2$ actually shows $C \in S(\mathfrak{G}_{s_1,s_2} \lor (\mathfrak{G}_{p_1} \cup \mathfrak{G}_{q_1}) \lor \cdots \lor (\mathfrak{G}_{p_k} \cup \mathfrak{G}_{q_k}))$. $\Box$

3. High minimum rank.

In this section, we extend the characterization of minimum rank equal to order for loopless loop graphs given in [16] to all loop graphs.

**Theorem 3.1.** For every loop graph $\mathfrak{G}$, $\text{mr}(\mathfrak{G}) = |\mathfrak{G}|$ if and only if $\mathfrak{G}$ has a unique spanning composite cycle.

**Proof.** If $\mathfrak{G}$ has a unique spanning composite cycle, then det $A \neq 0$ for all $A \in S(\mathfrak{G})$, so $\text{mr}(\mathfrak{G}) = |\mathfrak{G}|$. Now suppose that $\text{mr}(\mathfrak{G}) = |\mathfrak{G}|$. If $\mathfrak{G}$ is a loop graph without loops, then $\text{mr}(\mathfrak{G}) = \text{mr}_0(G)$, where $G$ denotes $\mathfrak{G}$ viewed as a simple graph and $\text{mr}_0(G)$ is the zero diagonal minimum rank as defined in [16], and the result is established by Theorem 3.9 of the same paper. Thus, we are left to consider the case when $\mathfrak{G}$ contains at least one loop. Suppose there is a loop graph $\mathfrak{G}$ with $\text{mr}(\mathfrak{G}) = |\mathfrak{G}|$ that does not have a unique spanning composite cycle. Let $\mathfrak{G}_* = (V_*, E_*)$ be a minimum counterexample in the sense that every loop graph $\mathfrak{G}$ on fewer than $|\mathfrak{G}_*|$ vertices having $\text{mr}(\mathfrak{G}) = |\mathfrak{G}|$ necessarily has a unique spanning composite cycle, and every loop graph on $|\mathfrak{G}_*|$ vertices with fewer edges also has this property. Denote the order of $\mathfrak{G}_*$ by $n_*$. Next, observe that $\mathfrak{G}_*$ has at least two spanning composite cycles, since at least one spanning composite cycle is guaranteed by Remark [4.1].

Now let $v$ be a vertex in $\mathfrak{G}_*$ such that $\ell := vv \in E(\mathfrak{G}_*)$. If $\ell$ is contained in every spanning composite cycle of $\mathfrak{G}_*$, then by deleting $\ell$ and $v$, there is a one-to-one correspondence between the spanning composite cycles of $\mathfrak{G}_*$ and those of $\mathfrak{G}_* - v$, so $\mathfrak{G}_* - v$ has at least two spanning composite cycles. We obtain $A(v) \in$
define the matrix $A$ polynomial of degree $n - t$ically zero. Hence, $\ell$ does not have a unique spanning composite cycle and $\mr(\ell) = |\ell|$. Since $\ell$ does not participate in any spanning composite cycle, this action does not affect the determinant. Again, $\ell$ is a smaller counterexample. Thus, we are left to consider the case when $H$ has both a spanning composite cycle $C(1)$ that contains $\ell$ and a spanning composite cycle $C(2)$ that doesn't contain $\ell$. Let $t = |E|$ and $Y = [y_{uv}]$ be a symmetric matrix of indeterminates $x_1, x_2, \ldots, x_t$ such that $\mathcal{G}(Y) = H$ (so $uv \in \mathcal{E}$ implies $y_{uv} = y_{wv} = x_i$ for some $x_i$); without loss of generality, let $y_{vv} = x_1$. Then the determinant of $Y$ is a homogeneous polynomial of degree $n_s$ in $x_1, x_2, \ldots, x_t$ and we can express it as

$$
\det Y = x_1p(x_2, \ldots, x_t) + q(x_2, \ldots, x_t)
$$

Further, since $\ell \in C(1)$ and $\ell \notin C(2)$, neither $p(x_2, \ldots, x_t)$ nor $q(x_2, \ldots, x_t)$ is identically zero. Hence, $p(x_2, \ldots, x_t)q(x_2, \ldots, x_t) \neq 0$. Thus, by \cite{16} Lemma 3.4, there exist nonzero real numbers $c_2, \ldots, c_t$ such that $p(c_2, \ldots, c_t)q(c_2, \ldots, c_t) \neq 0$. Now define the matrix $A$ by replacing $y_{uv} = x_i$ with $c_i$ for $i = 2, \ldots, t$ and $y_{vv} = x_1$ with $\frac{q(c_2, \ldots, c_t)}{p(c_2, \ldots, c_t)}$. Then $A \in \mathcal{S}(\ell)$ and $\det A = 0$ so $\mr(H) \leq \mr(A) \leq n_s - 1$, contradicting our assumption that $\mr(H) = n_s$. \qed

**Remark 3.2.** If $\mathcal{G}$ does not have a unique spanning composite cycle and there is a vertex $u$ of $\mathcal{G}$ such that $\mathcal{G} - u$ has a unique spanning composite cycle, then $\mr(\mathcal{G}) = |\mathcal{G}| - 1$.

**Example 3.3.** The converse of Remark 3.2 is false because $\mathcal{G}_4$, the path on four vertices with a loop at each vertex, has $\mr(\mathcal{G}_4) = 3$ but every induced subgraph on 3 vertices has minimum rank 2.

**4. Schur complement reduction.** In this section, we use the Schur complement to develop a reduction lemma that allows the removal of two vertices, reducing the order of the graph. This technique was used in \cite{24}. The next result is well known.

**Lemma 4.1.** \cite{26} p. 217 *Suppose that $A \in \mathbb{R}^{k \times k}$ is invertible, $B \in \mathbb{R}^{(n-k) \times k}$, and $D \in \mathbb{R}^{(n-k) \times (n-k)}$. Then

$$
\rank \begin{bmatrix} A & B^\top \\ B & D \end{bmatrix} = \rank \begin{bmatrix} A & 0 \\ 0 & D - BA^{-1}B^\top \end{bmatrix} = \rank A + \rank(D - BA^{-1}B^\top)
$$

For a loop graph $\mathcal{G}$ that does not have an edge between vertices $u$ and $v$ (this includes the case of a loop when $u = v$), $\mathcal{G} + uv$ denotes the loop graph obtained from
Case (1): Neither rank $C$. We then construct a matrix $A$ on the case, but in all cases so that $(\alpha, \alpha) = (x, x)$ is adjacent to $z$ in the loop configuration is such that $G$ by deleting vertices $y$ and $z$ and adding an edge between $x$ and $w$.

(1) If neither $y$ nor $z$ has a loop in $G$, then $mr(G) = mr(G') + 2$.

(2) If $z$ has a loop in $G$ but $y$ does not, then

$$mr(G) = \begin{cases} mr(G') + 2 & \text{if } x \text{ does not have a loop;} \\ \min\{mr(G'), mr(G' - xx)\} + 2 & \text{if } x \text{ has a loop.} \end{cases}$$

Proof. We can describe all cases as $mr(G) = mr(\mathcal{G}) + 2$, where $\mathcal{G}$ is $G'$ except with a loop or no loop on $x$ as specified. We establish the equality $mr(G) = mr(\mathcal{G}) + 2$ by showing that $mr(G) \geq mr(\mathcal{G}) + 2$ and $mr(G) \leq mr(\mathcal{G}) + 2$. Let $n := |G|$ and define the $2 \times (n - 2)$ matrix $B := \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \end{bmatrix}$. Order the vertices of $G$ so that $y, z, x, w$ are the first four vertices (in that order), choose any order for the remaining vertices, and let $\alpha := \{y, z\}$.

For the lower bound on $mr(G)$, we choose $A = [a_{ij}] \in S(\mathcal{G})$ with rank $A = mr(G)$ and partition $A$ as $\begin{bmatrix} A[\alpha] & A[\alpha, \alpha] \\ A[\alpha, \alpha]^{\top} & A[\alpha] \end{bmatrix}$. By Remark applied to the forest $\mathcal{T} = (\{x, y, z, w\}, \{xy, zw\})$, we may assume that $A[\alpha, \alpha]^\top = A[\alpha, \alpha] = B$. Since $y$ is adjacent to $z$ in $G$ and in all cases $y$ does not have loop in $G$, $A[\alpha]$ is invertible. We then define $C = A[\alpha] - A[\alpha, \alpha]A[\alpha]^{-1}A[\alpha, \alpha] = A[\alpha] - (A[\alpha]^{-1} \oplus 0)$. Note that $(A(\alpha))_{yw} = 0$ since $x$ and $w$ are not adjacent in $G$, so $C_{yw} = (A(\alpha))_{yw} - (A[\alpha]^{-1})_{yw} \neq 0$. In each case we show that the loop configuration is such that $C \in S(\mathcal{G})$. Then rank $A = rank C + 2$ by Lemma, so $mr(G) = rank A = rank C + 2 \geq mr(\mathcal{G}) + 2$.

For the upper bound on $mr(G)$, we choose a matrix $C = [c_{ij}] \in S(\mathcal{G})$ with rank $C = mr(\mathcal{G})$, noting that since $x$ is adjacent to $w$ in $G'$, so the entry $c_{yw}$ is nonzero. We then construct a matrix $A \in S(\mathcal{G})$ defined by $A[\alpha, \alpha]^\top = A[\alpha, \alpha] = B$ and $A(\alpha) = C + A(\alpha, \alpha)A[\alpha]^{-1}A[\alpha, \alpha] = C + (A[\alpha]^{-1} \oplus 0)$. The choice of $A[\alpha]$ depends on the case, but in all cases $A[\alpha]$ is invertible and $(A[\alpha])_{yz} \neq 0$; $A[\alpha]$ is chosen so that $(A(\alpha))_{yz} = C_{yz} + (A[\alpha]^{-1})_{yz} = 0$. In each case we show that the loop configuration is such that $A \in S(\mathcal{G})$. Then rank $A = rank C + 2$ by Lemma so $mr(G) \leq rank A = rank C + 2 = mr(\mathcal{G}) + 2$.

Case (1): Neither $y$ nor $z$ has a loop in $G$. For the lower bound on $mr(G)$, $A[\alpha]$ has the form $\begin{bmatrix} 0 & a_{yz} \\ a_{yz} & 0 \end{bmatrix}$ and $A[\alpha]^{-1} = \begin{bmatrix} 0 & \frac{1}{a_{yz}} \\ \frac{1}{a_{yz}} & 0 \end{bmatrix}$, so $C \in S(\mathcal{G}')$. For the upper bound
on \( mr(\mathcal{G}) \), define \( A[\alpha] := -\begin{bmatrix} 0 & \frac{1}{c_{xw}} \\ c_{xw} & 0 \end{bmatrix} \), so \( A \in S(\mathcal{G}) \).

**Case (2):** \( z \) has a loop in \( \mathcal{G} \) but \( y \) does not. For the lower bound on \( mr(\mathcal{G}) \), \( A[\alpha] = \begin{bmatrix} 0 & a_yz \\ a_yz & a_zz \end{bmatrix} \), which is invertible with \( A[\alpha]^{-1} = \frac{1}{\det A[\alpha]} \begin{bmatrix} a_zz & -a_yz \\ -a_yz & 0 \end{bmatrix} \). If \( x \) has no loop, then the \( x, x \)-entry of \( C \) is \( 0 - \frac{a_zz}{\det A[\alpha]} \), which is nonzero; if \( x \) has a loop, then the \( x, x \)-entry of \( C \) is \( a_{xx} - \frac{a_zz}{\det A[\alpha]} \), which can be zero or nonzero. Therefore,

\[
\text{mr}(\mathcal{G}) \geq \begin{cases} 
\text{mr}(\mathcal{G}' + xx) + 2 & \text{when } x \text{ has no loop;} \\
\min\{\text{mr}(\mathcal{G}'), \text{mr}(\mathcal{G}' - xx)\} + 2 & \text{when } x \text{ has a loop.}
\end{cases}
\]

For the upper bound on \( mr(\mathcal{G}) \), when \( x \) has no loop, let \( C = [c_{ij}] \in S(\mathcal{G}' + xx) \) be a matrix with rank \( C = \text{mr}(\mathcal{G} + xx) \). We define \( A[\alpha] := -\begin{bmatrix} c_{xx} & c_{xw} \\ c_{xw} & 0 \end{bmatrix}^{-1} \). Then \( A \in S(\mathcal{G}) \), establishing the upper bound in this subcase. Now assume that \( x \) has a loop, and let \( C = [c_{ij}] \) be a matrix in \( S(\mathcal{G}') \) or \( S(\mathcal{G}' - xx) \) with rank \( C = \min\{\text{mr}(\mathcal{G}'), \text{mr}(\mathcal{G}' - xx)\} \). We define \( A[\alpha] \) by

\[
A[\alpha] := \begin{cases} 
-\begin{bmatrix} 1 & c_{xw} \\ c_{xw} & 0 \end{bmatrix}^{-1} & \text{when } c_{xx} = 0; \\
-\begin{bmatrix} 2c_{xx} & c_{xw} \\ c_{xw} & 0 \end{bmatrix}^{-1} & \text{when } c_{xx} \neq 0.
\end{cases}
\]

Then \( A \in S(\mathcal{G}) \), so \( mr(\mathcal{G}) \leq \min\{\text{mr}(\mathcal{G}'), \text{mr}(\mathcal{G}' - xx)\} + 2 \). \( \square \)

**5. Minimum rank for families of graphs.** In this section, we establish the minimum rank of a loop graph consisting of a simple path \( P_n \), cycle \( C_n \), or complete graph \( K_n \) with an arbitrary configuration of loops. We use the symbol \( \mathcal{P}_n \) (respectively, \( \mathcal{C}_n \)) to denote \( P_n \) (respectively, \( C_n \)) with a given loop configuration, and \( \mathcal{R}_n^{(s)} \) to denote the loop graph obtained from the simple complete graph on \( n \) vertices by adding a loop to each of \( s \) vertices (so \( n - s \) vertices do not have loops); \( \mathcal{R}_n^{(s)} = \mathcal{R}_n \). When the vertices are numbered 1 to \( n \), we say a vertex or loop is odd or even according as the number of its vertex is odd or even.

**5.1. Path \( \mathcal{P}_n \).** A path is a tree, so \( M(\mathcal{P}_n) = Z(\mathcal{P}_n) \) \([22]\); thus, \( mr(\mathcal{P}_n) \) can be computed by using the zero forcing number. Here we give an explicit characterization. Given a path, a numbering of the vertices is defined by starting at one end with the number 1 and proceeding along the path, numbering the vertices consecutively (so \( \mathcal{P}_n \) has two numberings). Observe that for \( n \) odd, the parity of a vertex is the same in both numberings, whereas for \( n \) even the two numberings reverse the roles of odd
and even in addition to reversing the order of the vertices.

**Proposition 5.1.** For $n$ odd,

$$\text{mr}(P_n) = \begin{cases} n & \text{if } P_n \text{ has a unique odd loop;} \\ n - 1 & \text{otherwise.} \end{cases}$$

For $n$ even,

$$\text{mr}(P_n) = \begin{cases} n & \text{if all odd loops of } P_n \text{ come after all even loops;} \\ n - 1 & \text{otherwise.} \end{cases}$$

**Proof.** Note that $n - 1 = \text{mr}(P_n) \leq \text{mr}(P_n)$, and by Theorem 3.1, $\text{mr}(P_n) = n$ if and only if $P_n$ has a unique spanning composite cycle. First suppose $n$ is odd. Each odd loop $vv$ can be associated with one spanning composite cycle consisting of that loop and the edges (with endpoints) in perfect matching(s) of the component(s) of $P_n - v$, so $P_n = n$ if and only if $P_n$ has a unique odd loop. Now suppose $n$ is even. Then $P_n$ has a spanning composite cycle consisting of alternate edges, and has additional spanning composite cycle(s) if and only if $P_n$ has an odd loop before an even loop. \(\square\)

**5.2. Cycle $C_n$.** First note that $n - 2 = \text{mr}(C_n) \leq \text{mr}(C_n)$ (regardless of loop configuration). Given a cycle, a *numbering* of the vertices is defined by selecting one vertex to number 1 and proceeding around the cycle, numbering the vertices consecutively (a given cycle has many numberings). The property of having a numbering with a unique odd loop is used to characterize $\text{mr}(C_n)$, but first we need a lemma.

**Lemma 5.2.** $\text{mr}(C_n') = n - 2$.

**Proof.** The adjacency matrix $A_{C_n}$ has eigenvalues $2 \cos\left(\frac{2\pi k}{n}\right)$ for $k = 1, \ldots, n$ \([11]\) For $n \neq 4$, $\cos\left(\frac{2\pi}{n}\right) = \cos\left(\frac{2\pi(n-1)}{n}\right) \neq 0$, so $A_{C_n} - 2 \cos\left(\frac{2\pi}{n}\right)I \in S(C_n')$ and

$$\text{rank}(A_{C_n} - 2 \cos\left(\frac{2\pi}{n}\right)I) = n - 2 \geq \text{mr}(C_n').$$

For $n = 4$, $A = \begin{bmatrix} 2 & 1 & 0 & -1 \\ 1 & 1 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ -1 & 0 & -1 & 1 \end{bmatrix} \in \mathcal{S}(C_n')$ and $\text{rank} A = 2$. \(\square\)

**Observation 5.3.** If $n$ is even, then the underlying simple graph $C_n$ is bipartite, and $C_n$ has a numbering with exactly one odd loop if and only if at least one of the two partite sets has exactly one loop.
Theorem 5.4.

\[
\text{mr}(C_n) = \begin{cases} 
  n & \text{if } n \text{ is odd and } C_n \text{ has no loops;} \\
  n - 1 & \text{if } C_n \text{ has a numbering with exactly one odd loop;} \\
  n - 2 & \text{otherwise.}
\end{cases}
\]

If \( \text{mr}(C_n) = n - 1 \) then there exists a vertex \( v \) such that \( C_n - v \) has a unique spanning composite cycle. Furthermore, \( M(C_n) = Z(C_n) \) unless \( n \) is odd and \( C_n \) has no loops.

Proof. By Theorem 3.1, \( \text{mr}(C_n) = n \) if and only if \( C_n \) has a unique spanning composite cycle. If \( n \) is odd and \( C_n \) is loopless, then \( C_n \) has a unique spanning composite cycle and \( \text{mr}(C_n) = n \). If \( n \) is odd and \( C_n \) has at least one loop, then \( C_n \) has at least two spanning composite cycles (the cycle itself and a loop with a perfect matching on the remaining vertices), so \( \text{mr}(C_n) \leq n - 1 \). If \( n \) is even, then \( C_n \) has at least three spanning composite cycles (the cycle itself and two perfect matchings), so \( \text{mr}(C_n) \leq n - 1 \). If \( n \) is even and \( C_n \) has no loops, then \( \text{mr}(C_n) = \text{mr}_0(C_n) = n - 2 \) [10]. Henceforth, we assume \( C_n \) has a loop, and thus, \( n - 2 = \text{mr}(C_n) \leq \text{mr}(C_n) \leq n - 1 \).

Suppose \( C_n \) has a numbering with a unique odd loop; without loss of generality this loop is at vertex 1. We apply Proposition 5.1 to \( P_{n-1} := C_n - 2 \) to show that \( \text{mr}(C_n - 2) = n - 1 \), implying \( \text{mr}(C_n) \geq n - 1 \). We use the numbering of \( P_{n-1} \) determined by fixing 1 and renumbering everything else. If \( n \) is even, the vertices retain their parity under this renumbering and 1 is the only odd loop in \( P_{n-1} \), which has odd order. If \( n \) is even then fixing 1 and renumbering the remaining vertices causes all other vertices to change parity. Since 1 is the only odd loop in \( C_n \), there are no even loops in \( P_{n-1} \), which has even order, so vacuously every odd loop is after every even loop.

Now assume that \( C_n \) has a loop and no numbering has a unique odd loop. We show \( \text{mr}(C_n) = n - 2 \); note that this implies \( M(C_n) = Z(C_n) = 2 \), because any set of two consecutive vertices is a zero forcing set. The proof that \( \text{mr}(C_n) = n - 2 \) is by induction on the number of vertices using \( P_4 \) reduction (Lemma 12). A numbering on \( C_n \) naturally induces a numbering on \( C_n' \) by reducing every number greater than those assigned to \( y \) and \( z \) by two (\( C_n' \) denotes the graph produced by the reduction); this does not change the parity of any vertex or loop. Since \( P_4 \) reduction reduces the order by two, we consider \( n = 3 \) and \( n = 4 \) as the base cases. The case \( n = 3 \) is clear, because \( \text{mr}(C_3') = 1 \) and \( C_3' \) is the only loop configuration with at least one loop and no numbering having exactly one odd loop. For \( n = 4 \), the possible loop configurations are all loops (i.e., \( C_4' \)) or two nonadjacent loops; we denote the latter by \( C_4^{(2)} \). By Lemma 12, \( \text{mr}(C_4') = 2 \). For \( C_4^{(2)} \), define \( A := A_{C_4} + \text{diag}(-1, 0, 1, 0) \in S(C_4^{(2)}) \); rank \( A = 2 \) so \( \text{mr}(C_4^{(2)}) = 2 \).
Now assume the theorem holds for all $k$ with $3 \leq k \leq n-2$ and consider $\mathcal{C}_n$, which by assumption has a loop and no numbering has a unique odd loop. If $\mathcal{C}_n = \mathcal{C}_n'$, then $\text{mr}(\mathcal{C}_n) = n - 2$ by Lemma 5.2. If $\mathcal{C}_n$ has two consecutive vertices without loops, then we apply $P_4$ reduction with $y$ and $z$ as loopless vertices; $\mathcal{C}_n'$ inherits the property of not having a numbering with a unique odd loop, so we can apply the induction hypothesis. So assume $\mathcal{C}_n$ has at least one vertex with no loop and does not have two consecutive vertices without loops (in addition to assuming $\mathcal{C}_n$ has at least one loop and no numbering has a unique odd loop). We consider the cases $n$ even and $n$ odd separately.

Suppose first that $n$ is even, so $C_n$ is bipartite; denote the partite sets by $X$ and $Y$. In $\mathcal{C}_n$, neither $X$ nor $Y$ has exactly one loop and without loss of generality $Y$ has a loopless vertex. Select a loopless vertex $y \in Y$ and perform $P_4$ reduction. Define $X' := X \setminus \{z\}$ and $Y' := Y \setminus \{y\}$. Note that $Y'$ does not have exactly one loop. If $X$ has exactly two loops, they are on vertices $x$ and $z$, so $X'$ has no loops in $\mathcal{C}_n' - xx$. If $X$ has more than two loops, then $X'$ has at least two loops in $\mathcal{C}_n'$. So in one of $\mathcal{C}_n' - xx$ or $\mathcal{C}_n'$, neither $X'$ nor $Y'$ has exactly one loop, and we can apply induction to conclude that $\text{mr}(\mathcal{C}_n' - xx) = n - 4$ or $\text{mr}(\mathcal{C}_n') = n - 4$ and thus $\text{mr}(\mathcal{C}_n) = n - 2$.

Finally suppose $n$ is odd and examine the loop configuration of $\mathcal{C}_n$. We consider maximal segments of consecutive vertices all having loops, which we call loop segments. Recall that $\mathcal{C}_n$ has at least one loop and at least one vertex with no loop, does not have two consecutive vertices without loops, and no numbering has a unique odd loop. Because $n$ is odd and $n \geq 5$, these properties imply that $\mathcal{C}_n$ must have at least one of the following: (i) A loop segment with at least 4 vertices. (ii) Three or more separate loop segments with at least 2 vertices each. (iii) A loop segment with 3 vertices and a separate loop segment with at least 2 vertices. Choose $y$ to be a loopless vertex adjacent to a loop segment with the greatest number of vertices, and let $x$ denote the neighbor of $y$ in this loop segment. Apply $P_4$ reduction to obtain $\mathcal{C}_n'$. In each case, $\mathcal{C}_n'$ has a loop segment with 4 or more vertices or has at least two loop segments with 2 or more vertices. Either of these is sufficient to imply every numbering has at least two odd loops, so $\text{mr}(\mathcal{C}_n') = n - 4$ and thus $\text{mr}(\mathcal{C}_n) = n - 2$.

To establish the last statement it suffices to assume $\mathcal{C}_n$ has a numbering with a unique odd loop and exhibit a zero forcing set of one vertex; without loss of generality the unique odd loop is at vertex 1. Then $\{2\}$ is a zero forcing set: Since 2 is blue, 3 has exactly one white neighbor, 4, so $3 \rightarrow 4$. We continue this process with $2k + 1 \rightarrow 2k + 2$ as the $k$th force, for $1 \leq k \leq \left\lfloor \frac{n-2}{2} \right\rfloor$. Thus, all odd vertices except 1 are blue after $\left\lfloor \frac{n-2}{2} \right\rfloor$ forces. Then $1 \rightarrow 1$ if $n$ is even and $n \rightarrow 1$ if $n$ is odd. Since there are now two consecutive blue vertices, we can completely color the cycle. Thus, $1 \geq Z(\mathcal{C}_n) \geq M(\mathcal{C}_n) = 1$. \[\square\]
5.3. Complete graph $\mathcal{K}_n$ with deleted loops. The next result could be proved entirely from [16, Theorem 2.4] and Proposition 6.8 below, but instead we provide additional examples of optimal matrices.

**Proposition 5.5.**

$$\text{mr}(\mathcal{K}_n^{(s)}) = \begin{cases} 3 & \text{if } 3 \leq n - s; \\ 2 & \text{if } 1 \leq n - s \leq 2 \leq n; \\ 1 & \text{if } n - s = 0 \text{ and } 1 \leq n; \\ 0 & \text{if } n - s = 1 = n. \end{cases}$$

**Proof.** Let $k := n - s$ and suppose first that $k \geq 3$. Then $\mathcal{K}_3^{(0)}$ (the loopless complete graph on 3 vertices) is an induced subgraph of $\mathcal{K}_n^{(s)}$, and $\text{mr}(\mathcal{K}_3^{(0)}) = \text{mr}_0(K_3) = 3$ by [16, Theorem 2.4]. Thus, $\text{mr}(\mathcal{K}_n^{(s)}) \geq 3$. For $v \in \mathbb{R}^n$, let $(v)_i$ denote the $i$th coordinate of $v$. Define the vectors $v_1$ and $v_2$ in $\mathbb{R}^n$ by

$$(v_1)_i := \begin{cases} \sin \frac{i\pi}{n} & \text{if } i \leq k; \\ 1 & \text{if } i > k. \end{cases} \quad (v_2)_i := \begin{cases} \cos \frac{i\pi}{n} & \text{if } i \leq k; \\ 1 & \text{if } i > k. \end{cases}$$

Also define $v_3 := 1_n$, where $1_n$ is the all ones $n$-vector.

Then we claim the matrix $A := v_1v_1^\top + v_2v_2^\top - v_3v_3^\top$ is a matrix in $\mathcal{S}(\mathcal{K}_n^{(s)})$ and rank $A = 3$. Since $A$ is the sum of three rank one matrices, rank $A$ is less than or equal to 3. Therefore, it suffices to show $A \in \mathcal{S}(\mathcal{K}_n^{(s)})$. For $i, j \leq k$, $(A)_{ij} = \sin \frac{i\pi}{n} \sin \frac{j\pi}{n} + \cos \frac{i\pi}{n} \cos \frac{j\pi}{n} - 1 = \cos \frac{(i-j)\pi}{2(n+1)} - 1$, which is zero only when $i = j$. Thus, for $i > k$, $j \leq k$, $(A)_{ij} = \sin \frac{i\pi}{n} \sin \frac{j\pi}{n}$, which is zero only when $i = j$. For $i > k$, $j < k$, $(A)_{ij} = \sin \frac{i\pi}{n} \sin \frac{j\pi}{n} - 1 \neq 0$. For $i > k$, $j > k$, $(A)_{ij} = 1 + 1 - 1 = 1$.

In the case $n \geq 2 \geq k \geq 1$, it is clear that $\text{mr}(\mathcal{K}_n^{(s)}) \geq 2$, and a rank 2 matrix may be constructed as follows (with $J_m$ denoting the $m \times m$ all ones matrix): For $k = 1: \begin{bmatrix} J_{n-1} & 1_{n-1} \\ 1_{n-1}^\top & 0 \end{bmatrix}$. For $k = 2: \begin{bmatrix} 2J_{n-2} & 1_{n-2} & 1_{n-2}^\top \\ 1_{n-2}^\top & 0 & 1 \\ 1_{n-2} & 1 & 0 \end{bmatrix}$. In the case $k = 0, n \geq 1$, $J_n$ has rank 1, and in the case $k = 1 = n$, the matrix $[0]$ has rank 0.

6. Maximum rank and ranks in between.

In this section, we study the question of possible ranks for $A \in \mathcal{S}(\mathcal{G})$. It is well known that for any simple graph $G$, the maximum possible rank is the order of $G$, and every rank between the minimum and maximum ranks is realized by some $A \in \mathcal{S}(G)$. However, this is not true in the case of loop graphs. Given a loop graph $\mathcal{G}$, we say that $\mathcal{G}$ allows rank $r$ if there is a matrix $A \in \mathcal{S}(\mathcal{G})$ such that rank $A = r$, in which
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case \( A \) is said to realize rank \( r \) for \( \mathcal{S} \). The maximum rank of a loop graph \( \mathcal{G} \) is

\[
\text{MR}(\mathcal{G}) = \max \{ \text{rank} \ A : A \in S(\mathcal{G}) \}.
\]

A sign pattern matrix is a matrix with entries in \( \{+,-,0\} \) and a zero-nonzero pattern matrix is a matrix with entries in \( \{*,0\} \); here we consider only symmetric patterns. An order \( n \) loop graph \( \mathcal{G} \) is uniquely associated with an \( n \times n \) zero-nonzero pattern matrix \( Y_G \) where \( y_{uv} = * \) if \( uv \in E(\mathcal{G}) \), and \( y_{uv} = 0 \) otherwise. Each zero-nonzero pattern matrix \( Y \) describes a (finite) set of sign pattern matrices \( S_Y \), where \( S = [s_{uv}] \in S_Y \) if and only if \( s_{uv} = 0 \iff y_{uv} = 0 \). Taking the maximum rank over a set of matrices described by a zero-nonzero pattern matrix is equivalent to taking the maximum of the maximum ranks over all sign pattern matrices described by the zero-nonzero pattern matrix. Note that what we denote by MR for a loop graph (namely the maximum rank over symmetric matrices described by \( \mathcal{G} \)) is denoted by SMR when applied to a sign pattern or zero-nonzero pattern, to emphasize that only symmetric matrices are permitted, whereas MR does not require the matrices to be symmetric even when the pattern matrix is. There is substantial body of literature about sign patterns and their minimum and maximum ranks that can be applied (see [18, Section 42.6]). It is known that for a symmetric sign pattern matrix \( S \), \( \text{SMR}(S) = \text{MR}(S) \) [19]. So for a zero-nonzero pattern \( Y \), \( \text{SMR}(Y) = \text{MR}(Y) \).

The term-rank of a zero-nonzero or sign pattern matrix is the maximum number of nonzero entries no two of which are in the same line (same row or same column). For a sign-pattern \( S \), \( \text{MR}(S) \) is equal to the term-rank of \( S \) [18 Fact 42.6.1]. A composite cycle of order \( k \) in \( \mathcal{G} \) immediately yields a collection of nonzero entries of \( Y_G \) with no two in the same line, by choosing \( y_{uu} \) for a loop at vertex \( u \), \( y_{uv} \) and \( y_{vu} \) for edge \( uv \), and \( y_{u_1,u_2}, y_{u_2,u_3}, \ldots, y_{u_{k-1},u_k}, y_{u_k,u_1} \) for the cycle \( (u_1, \ldots, u_t, u_1) \). In a symmetric pattern matrix, a set of \( k \) nonzero entries \( y_{r_1,c_1}, \ldots, y_{r_k,c_k} \) of \( Y_G \) with no two in the same line yields a composite cycle of order at least \( k \). To see this, note that the entry \( y_{r_1,c_1} \) can be associated with the arc \( (r_1,c_1) \) in a digraph on the vertices \( \{1, \ldots, n\} \). Since no two of the entries are in the same line, the in-degree and out-degree of each vertex is at most one. Thus, each (weakly) connected component of the digraph is a directed path or directed cycle (allowing 1-cycles and 2-cycles as well as \( k \)-cycles with \( k \geq 3 \)). A directed cycle can be taken as part of a composite cycle (as a loop, edge, or cycle). Because the pattern is symmetric, a directed path on the vertices \( u_1, \ldots, u_t \) can be replaced by the graph edges \( u_2u_1, \ldots, u_{t+1}u_t \). The directed path has \( t - 1 \) directed edges (nonzero entries in \( Y_G \)), and the \( \lfloor \frac{t}{2} \rfloor \) graph edges cover \( t - 1 \) (if \( t \) is odd) or \( t \) (if \( t \) is even) vertices. Thus, \( \text{SMR}(Y_G) = \text{MR}(Y_G) = \text{term-rank}(Y_G) = \) the maximum order of a composite cycle of \( \mathcal{G} \). The next result follows from these equalities; it is also easily derivable from [14].
Proposition 6.1. Let $G$ be a loop graph and let $m$ denote the maximum order of a composite cycle of $G$. Then $MR(G) = m$.

Because the maximum order of a composite cycle of a subgraph is less than or equal to the maximum order of a composite cycle of a graph, the next corollary is immediate.

Corollary 6.2. If $H$ is a subgraph of $G$, then $MR(H) \leq MR(G)$.

If $B$ is a (necessarily loopless) bipartite graph, then rank $B$ is even for all $B \in S(B)$ \cite{10}, so it is possible for a loop graph $G$ to allow rank $k$, not allow rank $k+1$, and allow $k+2$. But it is not possible for $G$ to allow rank $k$, not allow rank $k+1$, not allow rank $k+2$, and allow $k+m$ for some $m \geq 3$. The next proposition follows from \cite{17} Theorem 5.4.

Proposition 6.3. Suppose $mr(G) \leq k \leq MR(G) - 1$. Then $G$ must allow rank $k$ or rank $k+1$.

If $G$ does not have a composite cycle of order $r$, then $G$ does not allow rank $r$, because $S_r(A) = 0$ for all $A \in S(G)$ (see Remark \cite{11}). Thus, it follows from Proposition 6.3 that for every $k$ between $mr(G)$ and $MR(G) - 1$, $G$ must have a composite cycle of order $k$ or order $k+1$. But this can be shown for all $k \leq MR(G) - 1$ (not just those greater than the minimum rank) by a different method.

Remark 6.4. Let $A$ be a real symmetric matrix. If all principal submatrices of $A$ of order $k$ and $k+1$ are singular, then rank $A \leq k - 1$. This was established in \cite{8} by a technical proof, and in \cite{11} it was observed that it follows from the fact that for any real symmetric matrix $A$, rank $A$ is the maximum $k$ such that $A$ has a $k \times k$ nonsingular matrix \cite{15} Corollary 8.9.2, and the fact that adding a row and column adds at most two to the rank.

Proposition 6.5. Suppose $G$ does not have a composite cycle of order $k$ or a composite cycle of order $k+1$. Then $G$ does not have a composite cycle of order $m$ for all $m \geq k$, and $MR(G) \leq k - 1$.

Proof. Since $G$ has neither a composite cycle of order $k$ nor a composite cycle of order $k+1$, for $A \in S(G)$, all principal submatrices of $A$ of order $k$ and $k+1$ are singular, so rank $A \leq k - 1$. Thus, $MR(G) \leq k - 1$, and by Proposition 6.1 $G$ has no composite cycle of order $m \geq k$.

Of course it is possible for the characteristic polynomial of a particular matrix to have several consecutive coefficients be zero and still have a nonzero determinant, but this must be caused by cancellation of terms, not by absence of composite cycles. Proposition 6.5 is not true for directed loop graphs: A loopless directed $n$-cycle has an $n$-cycle and no other composite cycles.
If $G$ does not have a composite cycle of order $r$, then $G$ does not allow rank $r$. In a bipartite loop graph (which necessarily has no loops), all composite cycles are even. The next example is a nonbipartite loop graph that has a gap in composite cycles between minimum and maximum ranks, and thus necessarily has a gap in realizable ranks.

**Example 6.6.** Let $G$ and $G'$ be the loop graphs shown in Figure 6.1. Since $G$ has a 3-cycle, $G$ is not bipartite. We will show that $mr(G) = 9$, $MR(G) = 12$, but there is no composite cycle of order 11, and thus, rank 11 is not realizable by any matrix in $S(G)$. Note that $G$ is loopless and $G'$ is an induced subgraph of $G$. Since $G'$ has a unique spanning composite cycle, $9 = mr(G') \leq mr(G)$. On the other hand, the graph $G$ can be covered by three copies of $C_4^0$ and one $C_3^0$, so

$$mr(G) \leq 3 \cdot mr(C_4^0) + mr(C_3^0) = 3 \cdot 2 + 3 = 9.$$ 

As a consequence, $mr(G) = 9$. We can easily find composite cycles of orders 9, 10, and 12 in $G$, implying $MR(G) = 12$. If $G$ had a composite cycle $C$ of order 11, then $C$ would contain an odd cycle or a loop, since 11 is odd. However, the triangle in the center is the only odd cycle. But by choosing the triangle, we see that the order of $C$ must be less than or equal to 9. Hence, we cannot find a composite cycle of order 11, and rank 11 is not realizable by any matrix in $S(G)$. Finally, Proposition 6.3 ensures rank 10 is realizable. In summary, the realizable ranks are 9, 10, and 12.

If $G$ does not allow rank $r$ for $mr(G) < r < MR(G)$, does this imply the absence of composite cycles of order $r$? The next example provides a negative answer.

**Example 6.7.** Let $\mathcal{H}$ be the loop graph $\mathcal{H}_3 = (x, y, z)$, with a loop on $y$. Let $\mathcal{B}_n$ be the loop graph obtained from $\mathcal{H}$ and $K_{n,n}$ by identifying vertex $z$ with a vertex of $K_{n,n}$; $\mathcal{B}_3$ is shown in Figure 6.2. It can be seen that this graph $\mathcal{B}_n$ has a composite cycle of every order ranging from 1 to $2n + 2 = |\mathcal{B}_n|$. Now we claim that the only realizable ranks are $\{4, 6, \ldots, 2n + 2\}$. That is, no odd number between 4 and $2n + 2$ can be realized.

To see this, we set $x$ and $y$ to be the first and the second vertices and use Remark 1.3 to scale the matrix. Henceforth, we may assume any matrix $A \in S(\mathcal{B}_n)$ has the

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**Fig. 6.1.** The graph $G$ for Example 6.6 and its induced subgraph $G'$. 

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form
\[ A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 1 & 1 & 1 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix} \oplus \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ 0 & 0 & \cdots & \cdots & 0 \end{bmatrix}, \]

where \( M \in S(\mathfrak{S}_{n,n}) \). By subtracting the first row/column from the third row/column, we obtain the matrix \( B := [A \ A] \oplus M \), so \( \text{rank } B = \text{rank } A = \text{rank } M + 2 \). Since we know \( M \in S(\mathfrak{S}_{n,n}) \) and the realizable ranks of \( M \) are \( \{2, 4, \ldots, 2n\} \), the realizable ranks of \( B \) are
\[ \{2, 4, \ldots, 2n\} + 2 = \{4, 6, \ldots, 2n + 2\}. \]

We now consider adding a new vertex adjacent to all existing vertices. The ideas in the proof are similar to those in [16, Theorem 4.6], but since we expand it to include the case of a new vertex with a loop, we include the brief proof.

**Proposition 6.8.** Suppose \( \mathfrak{S} \) is a loop graph of order \( n \) such that \( \delta(\mathfrak{S}) \geq 1 \), and that the graph \( \mathfrak{G} \) is constructed from \( \mathfrak{S} \) by joining a single vertex \( v \) (with or without a loop) to \( \mathfrak{S} \). Suppose \( \mathfrak{S} \) allows rank \( k \). Then \( \mathfrak{G} \) allows rank \( k + 1 \), and if \( v \) has a loop then \( \mathfrak{G} \) allows rank \( k \).

**Proof.** Given \( A \in S(\mathfrak{S}) \) with rank \( A = k \), we can construct a matrix \( \tilde{A} \in S(\mathfrak{G}) \) with rank \( \tilde{A} = k + 1 \) as follows, and if the new vertex \( v \) has a loop, the rank \( k \) matrix \( B \) constructed is also in \( S(\mathfrak{G}) \). Without loss of generality, let the new vertex be \( n + 1 \). Since \( \delta(\mathfrak{S}) \geq 1 \), every row of \( A \) has a nonzero entry. By [16, Lemma 4.5], we can choose a real vector \( x \) such that every entry of \( Ax \) is nonzero and \( x^T Ax \neq 0 \). Let \( B := \begin{bmatrix} A & Ax \\ x^T & x^T Ax \end{bmatrix} \). Then rank \( B = \text{rank } A = k \), and if \( v \) has a loop \( B \in S(\mathfrak{G}) \).
We can change the entry $x^TAx$ to either 0 or $2x^TAx$ so that $\tilde{A} = \begin{bmatrix} A & Ax \\ x^TA & 0 \end{bmatrix}$ or $\tilde{A} = \begin{bmatrix} A & Ax \\ x^TA & 2x^TAx \end{bmatrix}$. Then $\tilde{A} \in \mathcal{S}(\mathfrak{G})$ and rank $\tilde{A} = k + 1$.

**Corollary 6.9.** $\mathfrak{R}_n^{(s)}$ allows all ranks $r$ such that $mr(\mathfrak{R}_n^{(s)}) \leq r \leq n = MR(\mathfrak{R}_n^{(s)})$.

**Proof.** By Proposition 6.8 when we add a vertex with a loop, we may choose to leave the rank unchanged or increase it by one. Suppose first that $n - s \geq 3$. Consider the induced subgraph obtained by taking all of the loopless vertices; this subgraph is $\mathfrak{R}_n^{(0)}$. Since the subgraph has no loops, it must allow all ranks $r$ such that $mr(\mathfrak{R}_n^{(0)}) = 3 \leq r \leq (n - s)$ by Corollary 4.7 in [16]. Then $\mathfrak{R}_n^{(s)}$ can be obtained by joining $s$ looped vertices to $\mathfrak{R}_n^{(0)}$ without raising the rank, so $\mathfrak{R}_n^{(s)}$ allows rank $r$ for all $r$ such that $mr(\mathfrak{R}_n^{(s)}) \leq r \leq (n - s)$. For $r$ with $(n - s) \leq r \leq n$, construct an $(n - s) \times (n - s)$ matrix with full rank in $\mathcal{S}(\mathfrak{R}_n^{(0)})$. By joining $r - (n - s)$ looped vertices while increasing rank by one at each step, we obtain a rank $r$ matrix in $\mathcal{S}(\mathfrak{R}_n^{(r - (n - s))})$. We then join $(n - r)$ additional looped vertices to obtain $\mathfrak{R}_n^{(s)}$ without increasing the rank. Therefore, $\mathfrak{R}_n^{(s)}$ allows all ranks $r$ such that $mr(\mathfrak{R}_n^{(s)}) \leq r \leq n = MR(\mathfrak{R}_n^{(s)})$. The case $n - s \leq 2$ is similar.

**Observation 6.10.** Since $n - 1 \leq mr(\mathfrak{P}_n) \leq MR(\mathfrak{P}_n) \leq n$, $\mathfrak{P}_n$ trivially allows all ranks $r$ such that $mr(\mathfrak{P}_n) \leq r \leq MR(\mathfrak{P}_n)$.

**7. Additional topics and future research.** In this section, we discuss extensions to loop graphs of additional results for simple graphs and pose open questions for future research.

**7.1. Extreme minimum rank.** Recall that a loop graph has minimum rank equal to its order if and only if it has a unique spanning composite cycle. It is well-known that for a simple graph $G$, $mr(G) = |G| - 1$ if and only if $G$ is a path.

**Question 7.1.** What loop graphs $\mathfrak{G}$ have $mr(\mathfrak{G}) = |\mathfrak{G}| - 1$?

Results in Section 5 characterize the loop configurations of paths and cycles with minimum rank one less than order, but in general the question is open.

Minimum rank three has been characterized for loopless loop graphs (zero diagonal minimum rank) in [16] and it may be productive to investigate minimum rank three for other loop configurations (such as all loops).

**Question 7.2.** What loop graphs $\mathfrak{G}$ have $mr(\mathfrak{G}) = 3$?

However, it is known that for simple graphs there is an infinite family of forbidden
induced subgraphs for minimum rank three \[20\].

7.2. Minimum rank of additional families and small loop graphs. The AIM Minimum Rank Catalog \[1\] lists the minimum rank of more than forty families of graphs. Extensions of these results to loop graphs could be investigated, including some very well-known graphs such as complete bipartite graphs.

Since the question of whether a loop graph has minimum rank equal to zero or one is easily answered, by applying the forbidden subgraph test one can determine for a loop graph whether minimum rank is equal to 0, 1, 2, or is \(\geq 3\). For any loop graph of order \(n\) the unique spanning composite cycle test determines whether the graph has minimum rank \(n\) or \(\leq n - 1\). These tests immediately determine the minimum rank of all loop graphs of order at most four. Furthermore, if the zero forcing number lower bound equals the unique spanning composite cycle test upper bound, then the minimum rank is determined. These bounds have been implemented in the program \[23\], and work continues to add additional methods to this program, such as checking for graphs for which the minimum rank can be determined by other methods discussed in this paper, such as trees (mr(\(T\)) = |\(T\)| − \(Z(\tau)\)) and cycles (Theorem \[5.4\]), and applying cut-vertex reduction \[25\] and \(P_4\) reduction (Lemma \[4.2\]). This will give the software the capability to determine the minimum rank of most loop graphs of order five and possibly order six, at which point it may be feasible to complete the determination of minimum rank of loop graphs of order five (or six) by construction of matrices realizing the lower bounds, as was done for simple graphs of order at most seven in \[13\].

7.3. No useful Colin de Verdière type parameters. In this section, we present an example that shows that a Colin de Verdière type parameter, i.e. a minor monotone lower bound on maximum nullity defined using the Strong Arnold Hypothesis, is unlikely to exist. Definitions of Colin de Verdière type parameters, minor monotonicity, and the Strong Arnold Hypothesis can be found in \[3\] or \[14\].

Example 7.3. Let \(\mathcal{F}\) be the party hat graph in Figure 7.1. Then \(\{1\}\) is a zero forcing set for \(\mathcal{F}\) with a forcing process \(4 \rightarrow 5, 6 \rightarrow 2, 3 \rightarrow 3, 1 \rightarrow 4, 2 \rightarrow 6\). Thus, \(M(\mathcal{F}) \leq Z(\mathcal{F}) \leq 1\). But \(\mathcal{F}\) contains \(K_3\) and \(M(\mathcal{F}) = 1 < 2 = 3 - 1 = M(\mathcal{F}_3)\).

Since any matrix that has all entries nonzero, including a rank one matrix, satisfies the Strong Arnold Hypothesis, the Strong Arnold Hypothesis does not seem to imply minor monotonicity for loop graphs. Example 7.3 also implies that any minor monotone parameter \(\beta\) with \(\beta \leq M\) must have \(\beta(\mathcal{F}_3) \leq 1\), so any minor monotone parameter below \(M\) seems unlikely to be useful.
7.4. GCC is not true for loop graphs. The Graph Complement Conjecture (GCC) for simple graphs \[14\] is

\[\text{mr}(G) + \text{mr}(\overline{G}) \leq |G| + 2.\]

GCC is not true for loop graphs, as the next example shows.

Example 7.4. Consider the path on 4 vertices \(P_4\) with loops on the two middle vertices, which is shown in Figure 7.2. Observe that \(P_4\) is self complementary and \(\text{mr}(P_4) = 4\) by Proposition 5.1 so

\[\text{mr}(P_4) + \text{mr}(\overline{P_4}) = 4 + 4 = 8 > 6 = |P_4| + 2.\]

However, the question of whether there is a bound with a different additive constant remains open (see \[9\] for the analogous question for simple graphs).

Question 7.5. Does there exist a positive integer \(d\) such that for all \(G\),

\[\text{mr}(G) + \text{mr}(\overline{G}) \leq |G| + d?\]
Example 7.4 shows that if such $d$ exists then $d \geq 4$.

7.5. The $\delta$ Conjecture is not true for loop graphs. The $\delta$ Conjecture for simple graphs [13] is $\delta(G) \leq M(G)$. The $\delta$ Conjecture is not true for loop graphs, because $\delta(C_3) = 2 > 0 = M(C_3^0)$. Since in the loopless case, we are reducing the minimum number of nonzero entries per row, arguably the “$\delta$ Conjecture for loop graphs” should be $\delta(G) - 1 \leq M(G)$. However, $C_3^0$ (or any odd cycle with no loops) is still a counterexample, and illustrates the importance of symmetry (there is a nonsymmetric matrix with the same nonzero pattern and rank two).

7.6. Minimum rank over other fields. In this section, we discuss extension of our results in prior sections to fields other than the real numbers.

Low minimum rank over other fields. Barrett, van der Holst, and Loewy’s characterization of minimum rank at most two (quoted here in Theorem 2.2) applies to all infinite fields of characteristic not two, and the proof of Theorem 2.3 remains valid for infinite fields of characteristic not two, characterizing loop graphs having minimum rank at most two over such fields.

Barrett, van der Holst, and Loewy also have characterizations for infinite fields of characteristic two [5] and for finite fields [6]. These results provide tools that may allow characterizing minimum rank at most two over finite fields or fields of characteristic two.

High minimum rank over other fields. For minimum rank equal to order of the loop graph, the situation is entirely different for fields of characteristic two, because a $k$-cycle with $k \geq 3$ does not contribute to the determinant due to the fact that a $k$-cycle contributes $2 \equiv 0 \pmod{2}$ equal terms. For example, if $\text{char } F = 2$, then $\text{mr}_F(C_{2s+1}^0) = 2s$, despite the fact that $C_{2s+1}^0$ has a unique spanning composite cycle.

In addition to assuming characteristic not two, the proof that a loopless loop graph has minimum rank equal to its order if and only if it has a unique spanning composite cycle [16, Theorem 3.9] uses the fact that we can find nonzero field elements producing a nonzero value of a polynomial [16, Lemma 3.4]; this property is valid for infinite fields. But the proof of [16, Theorem 3.9] also uses the quadratic formula to extract a square root within the field [16, Lemma 3.5]. In the real numbers this is achieved by showing that the number whose square root is being extracted can be made positive. Thus, the proof does not immediately extend to proper subfields of the real numbers, such as the rationals. But it does extend to algebraically closed fields of characteristic not two (which are necessarily infinite). The proof of our Theorem 3.1 generalizing this to all loop graphs remains valid for any infinite field of characteristic two.
not two whenever the loopless base case is established. Thus, Theorem 3.1 is valid for algebraically closed fields of characteristic not two, in addition to the real numbers.

**Question 7.6.** Is there an example of loop graph $\mathcal{G}$ that does not have a unique spanning composite cycle and a (finite) field $F$ with char $F \neq 2$ such $\text{mr}^F(\mathcal{G}) = |\mathcal{G}|$?

Such an example, if one exists, is likely loopless, since if there is a loop that is in one spanning composite cycle and not in another then $\text{mr}^F(\mathcal{G}) < |\mathcal{G}|$ (because one can solve a linear equation).

**Schur complement techniques over other fields.** The use of the Schur complement in Lemma 4.1 is well known to be valid over any field. The proof of Lemma 4.2 ($P_4$ reduction) remains valid over any field with at least 3 elements; the only case where 3 are needed is in the construction of $A[\alpha]$ for the upper bound in the case $c_{xx} \neq 0$, where we need to avoid both 0 and $-c_{xx}$.

**Maximum and realizable ranks over other fields.** Much of the discussion in Section 6 relies on composite cycles, so we assume char $F \neq 2$. An infinite field suffices to ensure that any polynomial that is not identically zero can be made nonzero by a choice of values. With the exception of Corollary 6.9 all the results in Section 6 are valid for infinite fields of characteristic not two. Corollary 6.8 is valid for all fields of characteristic zero, because the proof of the loopless case in [16] constructs integer matrices.

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**REFERENCES**


