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Semiregular Trees with Minimal Laplacian Spectral Radius

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Abstract

A semiregular tree is a tree where all non-pendant vertices have the same degree. Among all semiregular trees with fixed order and degree, a graph with minimal (adjacency / Laplacian) spectral radius is a caterpillar. Counter examples show that the result cannot be generalized to the class of trees with a given (non-constant) degree sequence.

Key words: graph Laplacian, adjacency matrix, eigenvectors, spectral radius, Perron vector, tree

1991 MSC: 05C35, 05C75, 05C05, 05C50

1 Introduction

Let $G(V, E)$ be a simple connected undirected graph with vertex set $V(G)$ and edge set $E(G)$. The spectral radius of the adjacency matrix $A(G)$ of $G$ (also called the index of $G$) has been intensively studied. Hence there exists a vast literature that provides upper and lower bounds on the spectral radius of $G$ given some graph invariants and characterize the corresponding extremal graphs, see, e.g., [6]. Similarly, the eigenvalues of the Laplacian matrix $L(G)$

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of $G$, defined as $L(G) = A(G) - D(G)$ with degree matrix $D(G)$, have been investigated.

It is well known that a tree with given order has maximal (adjacency and Laplacian) spectral radius if and only if it is a star, and it has minimal spectral radius if and only if it is a path. However, it has only recently been shown that within the class of trees with a given degree sequence, extremal graphs have a ball-like structure where vertices of highest degrees are located near the center. Such trees can easily be found using a breadth-first search algorithm, see [2]. Zhang [15] has shown that this result also holds for the spectral radius of the Laplacian (and signless Laplacian) of trees with a given degree sequence. This result can be generalized to the so called $p$-Laplacian, see [4].

Analogous results for graphs which have minimal spectral radius are, however, rare. Stevanović and Hansen [12] looked at the class of connected graphs of given order and maximum clique size $\omega$. The resulting graph with minimal index are as long as possible, i.e., it consists of a clique of size $\omega$ with a path attached. Yuan et al. [14] have shown that among all trees with given order and maximum degree $\Delta$, comets have minimal Laplacian spectral radius, i.e, stars with central degree $\Delta$ with a path attached. Graphs with minimal index in the class of graphs with given order and diameters have been partly characterized by van Dam and Kooij [13] and Cioabă et al. [5]. Liu et al. [8] show similar results for trees with minimal Laplacian spectral radius and some given diameters.

In this paper we are interested in trees with minimal spectral radius when the degree sequence is given. Recall that a vertex of degree 1 is called a pendant vertex (or leaf) of a tree. We call a tree $G$ $d$-semiregular when all of its non-vertex vertices have degree $d$. We denote the class of $d$-semiregular trees with $n$ vertices by $T_{d,n}$. We assume throughout the paper that $d \geq 3$ (otherwise $G \in T_2,n$ is simply a path with $n$ vertices). Recall that a caterpillar is a tree where the subtree induced by all of its non-vertex vertices is a path. We denote the uniquely defined caterpillar in $T_{d,n}$ by $C_{d,n}$.

Recently Belardo et al. [1] have investigated $d$-semiregular trees with small spectral radius.

**Theorem 1** ([1])  A tree $G$ has smallest index in class $T_{d,n}$ if and only if it is a caterpillar $C_{d,n}$.

We show that the same result also holds for the graph Laplacian and the signless Laplacian $Q(G) = A(G) + D(G)$.

**Theorem 2**  A tree $G$ has smallest (signless) Laplacian spectral radius in class $T_{d,n}$ if and only if it is a caterpillar $C_{d,n}$.
If the given degree sequence is not constant, then the structure of extremal trees is more complicated. Section 3 gives some examples of extremal graphs that are not caterpillars.

In this paper we prove Theorem 2 with a technique where we use graph perturbations that are “inverse” to that of [15]. The same idea can also be applied for an alternative proof of Theorem 1, see Remark 9 below.

Remark 3 It is interesting to note that Simić et al. [11] have shown with a similar technique that caterpillars have maximal spectral radius among the trees with a fixed order and diameter [11].

2 Proof of Theorem 2

It is well-known that the signless Laplacian and the Laplacian of a tree have the same spectrum. Thus it is sufficient to prove Theorem 2 for the signless Laplacian.

Let \( \lambda(G) \) denote the largest eigenvalue of \( Q(G) \). As \( G \) is connected, \( Q(G) \) is irreducible and thus \( \lambda(G) \) is simple and there exists a unique positive eigenvector \( f_0 \) with \( ||f_0|| = 1 \) by the Perron-Frobenius Theorem (see, e.g., [7]). We refer to such an eigenvector as the Perron vector of \( G \). Remind that \( f_0 \) fulfills the eigenvalue equation

\[
(\lambda - d_G(v)) f_0(v) = \sum_{uv \in E} f_0(u)
\]

where \( d_G(v) \) denotes the degree of \( v \). Moreover, by the Rayleigh-Ritz Theorem \( f_0 \) maximizes the Rayleigh quotient for non-zero vectors \( f \) on \( V(G) \) defined as

\[
R_G(f) = \frac{\langle Qf, f \rangle}{\langle f, f \rangle} = \frac{\sum_{uv \in E} (f(u) + f(v))^2}{\sum_{v \in V} f(v)^2}.
\]

In particular, for any positive function \( f \) with \( ||f|| = 1 \) we find

\[
\lambda(G) = \sum_{uv \in E} (f_0(u) + f_0(v))^2 \geq \sum_{uv \in E} (f(u) + f(v))^2
\]

where equality holds if and only if \( f = f_0 \). Recall that \( \lambda(G) > 2 \) if \( G \neq K_1, K_2 \) and thus every pendant vertex of \( G \) is a strict local minimum of \( f_0 \).

We use the following approach for proving Theorem 2: For any tree \( G \) in \( T_{d,n} \) we construct a positive function \( f \) such that \( R_G(f) \geq R_{C_{d,n}}(f_0) \) where \( f_0 \) denotes the Perron vector of the caterpillar \( C_{d,n} \). Then we find \( \lambda(G) \geq R_G(f) \geq R_{C_{d,n}}(f_0) = \lambda(C_{d,n}) \) and we are done when either one of the inequalities is
strict or \( f \) does not fulfill the eigenvalue equation (1). Vector \( f \) is constructed by starting with Perron vector \( f_0 \) on \( C_{d,n} \) and rearranging the edges of the caterpillar until we arrive at \( G \). \( f \) and \( f_0 \) have then the same valuations but different Rayleigh quotients.

First we summarize the notion used for our construction: We write \( u \sim v \) if the vertices \( u \) and \( v \) are adjacent, i.e., if \( uv \in E(G) \). \( d_G(v) \) denotes the degree of \( v \) in \( G \), while \( d^*_G(v) \) is the number of non-pendant vertices that are adjacent to \( v \). For two adjacent non-pendant vertices \( v \sim u \) the branch \( B_{vu} \) is the subtree induced by \( v \) and all vertices of the component of \( G \setminus \{vu\} \) that contains \( u \). The length \( \ell(B_{vu}) \) of a branch is the number of its non-pendant vertices (which are the trunk vertices of \( G \)). We call a vertex \( v \) with \( d^*_G(v) \geq 3 \) a branching point of \( G \), and a non-pendant vertex \( v \) with \( d^*_G(v) = 1 \) a bud of \( G \). We call a branch with exactly one branching point \( v^* \) (and exactly one bud vertex) a proper branch. A positive function \( f \) on \( G \) is called unimodal with maximum \( \hat{v} \) if it is monotonically non-increasing on every path in \( G \) starting at \( \hat{v} \) and non-constant except (possibly) on just one edge incident to \( \hat{v} \).

The atomic steps of our rearrangement are switching of edges which have already been used by various authors, e.g., [9]: Let \( P \) be the path \( u_1^0v_1\ldots v_2u_2 \) in \( G \in \mathcal{T}_{d,n} \) where \( u_1^0 \) is a pendant vertex, \( d^*_G(v_2) \geq 2 \) and \( v_1 \neq v_2 \). Then we get a new tree \( G' \in \mathcal{T}_{d,n} \) by replacing edges \( v_1u_1^0 \) and \( v_2u_2 \) by the respective edges \( v_1u_2 \) and \( v_2u_1^0 \), see Fig. 1. For a unimodal function \( f \) on \( G \) with \( f(v_1) \geq f(v_2) \) we construct a function \( f' \) on \( G' \) by \( f'(u_1^0) = \min(f(u_1^0), f(u_2)) \), \( f'(u_2) = \max(f(u_1^0), f(u_2)) \), and \( f'(x) = f(x) \) for all other vertices. Notice that switching does not change the number of pendant and non-pendant vertices.

**Lemma 4** Let \( G \in \mathcal{T}_{d,n} \) and \( f \) be a unimodal function on \( G \) with maximum \( \hat{v} \). Construct \( G' \) and \( f' \) as described above. If \( f(v_1) \geq f(v_2) \), then \( f' \) is again unimodal with maximum \( \hat{v} \) and \( \mathcal{R}_{G'}(f') \geq \mathcal{R}_G(f) \). The inequality is strict if and only if either \( f(v_1) > f(v_2) \) and \( f(u_1^0) < f(u_2) \), or \( f(u_1^0) > f(u_2) \).
Proof. Unimodality of $f$ and $f(v_1) \geq f(v_2)$ implies $f(v_2) > f(u_2)$ and $f(v_1) \geq f(u_1^*)$. Assume first that $f(u_1^*) \leq f(u_2)$. Then $f'(x) = f(x)$ for all $x \in V(G)$ and by switching edges $v_1u_1^*$ and $v_2u_2$ with $v_1u_2$ and $v_2u_1^*$ we find (for $||f|| = 1$)

$$R_{G'}(f') - R_G(f) = \sum_{xy \in E \setminus E'} (f'(x) + f'(y))^2 - \sum_{uv \in E \setminus E'} (f(u) + f(v))^2$$

$$= (f(v_1) + f(u_2))^2 + (f(v_2) + f(u_1^*))^2$$

$$- (f(v_1) + f(u_1^*))^2 - (f(v_2) + f(u_2))^2$$

$$= 2(f(v_1) - f(v_2)) \cdot (f(v_2) - f(u_1^*)) \geq 0$$

where the inequality is strict whenever $f(v_1) > f(v_2)$ and $f(u_1^*) < f(u_2)$.

If $f(u_1^*) > f(u_2)$, then we have $f'(u_1^*) = f(u_2)$, $f'(u_2) = f(u_1^*)$, and $f'(x) = f(x)$ otherwise. Let $w_j, j = 1, \ldots, d_G(u_2) - 1$, be the neighbors of $u_2$ not equal to $v_2$. Then

$$R_{G'}(f') - R_G(f) = \sum_{w_j}(f'(u_2) + f'(w_j))^2 - \sum_{w_j}(f(u_2) + f(w_j))^2$$

$$= \sum_{w_j}[(f(u_1^*)^2 - f(u_2)^2) + 2(f(u_1^*) - f(u_2))f(w_j)] > 0.$$

Unimodality for $f'$ follows from the fact that monotonicity of $f$ on paths in $G$ that start at $v_1$ or $v_2$ is preserved at the corresponding paths in $G'$. \qed

Now if a tree $G$ has no branching point, then it is necessarily a caterpillar. Otherwise, there is a branching point $v^*$ with (at least) two proper branches $B_{v^*u_2}$ and $B_{v^*x_1}$, see Fig. 2. Let $v_2$ be the bud of $B_{v^*x_1}$ and $u_1^* \sim v_2$ a pendant vertex. Then we can switch edges $v^*u_2$ and $v_2u_1^*$ with $v^*u_1^*$ and $v_2u_2$ and obtain a $d$-semiregular tree $G'$ with $d_{G'}^*(v^*) = d_{G}^*(v^*) - 1 \geq 2$ and $d_{G'}^*(v_2) = d_{G}^*(v_2) + 1 = 2$ while $d^*(x)$ remains unchanged for all other non-pendant vertices $x$. Hence the number of buds and consequently the number of proper branches is reduced by 1. We call such a rearrangement a branch reduction for $G$ with reduction point $v^*$. We call the set of vertices in $B_{v^*u_2} \cup B_{v^*x_1}$ the fork of the branch reduction. A branch reduction is called minimal if its fork is minimal among all possible branch reductions.

We can repeat such steps until a caterpillar remains. Thus we arrive at the following

**Lemma 5** For every tree $G \in \mathcal{T}_{d,n}$ there exists a sequence of branch reductions

$$G = G_t \rightarrow G_{t-1} \rightarrow \cdots \rightarrow G_1 \rightarrow G_0 = C_{d,n}$$

(4)

that transforms $G$ into caterpillar $C_{d,n}$.

The switchings of these branch reductions can be reverted. Thus we obtain a
sequence of graph rearrangements that transforms $C_{d,n}$ back into tree $G$,

$$C_{d,n} = G_0 \rightarrow G_1 \rightarrow \cdots \rightarrow G_{t-1} \rightarrow G_t = G.$$  

Notice that caterpillar $C_{d,n}$ is symmetric about either a central vertex $v_c$ or a central edge $e_c$ (depending whether the number of vertices in the trunk is even or odd). This also holds for Perron vector $f_0$, since otherwise we could create a different Perron vector by reflecting the values of $f_0$ at $v_c$ and $e_c$, respectively.

**Lemma 6** The Perron vector $f_0$ of $C_{d,n}$ is unimodal with maximum in $v_c$ or $e_c$.

**Proof.** Let $v_1, \ldots, v_k$ denote the non-pendant vertices of $C_{d,n}$ such that $v_i \sim v_{i+1}$, and let $v_0 \sim v_1$ and $v_{k+1} \sim v_k$ be two pendant vertices. By (1) we find $(\lambda - 1)f_0(v_i^o) = f_0(v_i)$ for all pendant vertices $v_i^o$ adjacent to $v_i$ and thus

$$
\left(\frac{d-2}{\lambda-1}\right)f_0(v_i) = f_0(v_{i-1}) + f_0(v_{i+1}) \quad \text{for all } i = 1, \ldots, k.
$$

Since $f_0$ must obtain its maximum on the trunk, there is some vertex $v_j$ that satisfies $\left(\frac{d-2}{\lambda-1}\right)f_0(v_j) = f_0(v_{j-1}) + f_0(v_{j+1}) < 2f_0(v_j)$, and hence $\left(\frac{d-2}{\lambda-1}\right) < 2$. Now suppose $f_0$ is not strictly monotone on a path starting at a maximum of $f_0$. Then there exists a saddle point $v_s$ of $f_0$, that is, $\left(\frac{d-2}{\lambda-1}\right)f_0(v_s) = f_0(v_{s-1}) + f_0(v_{s+1}) \geq 2f_0(v_s)$, and thus $\left(\frac{d-2}{\lambda-1}\right) \geq 2$, a contradiction. $\Box$

Now let $C_{d,n} = G_0 \rightarrow G_1$ be the inverse of the last branch reduction in sequence (4) with reduction point $v^*$. Then $G_1$ has three proper branches $B_{v^*v_1}$, $B_{v^*v_2}$, and $B_{v^*v_3}$ with respective lengths $\ell_1 \geq \ell_2 \geq \ell_3$. 

![Fig. 2. Branch reduction: branch $B_{v^*v_2}$ in $G$ has been replaced by a leaf in $G'$. (Dashed lines are paths in $G$ and $G'$, respectively, and need not be edges. Further details omitted.)](image-url)
Lemma 7 Let \( k \) denote the number of non-pendant vertices of \( C_{d,n} \). Assume that no proper branch of \( G_1 \) contains more trunk vertices than the union of the remaining two branches, i.e., \( \ell(B_{v_{\ast,n}}) \leq \lceil \frac{k+1}{2} \rceil \) for all proper branches of \( G_1 \). Then there exists a unimodal function \( f_1 \) on \( G_1 \) with maximum in branching point \( v^* \) such that \( \mathcal{R}_{G_1}(f_1) \geq \mathcal{R}_{G_0}(f_0) = \lambda(C_{d,n}) \).

**Proof.** Let \( v_0 \) be either \( v_c \) or incident to \( e_c \). By symmetry and Lemma 6, \( v_0 \) is a maximum of \( f_0 \) and \( C_{d,n} \) has two branches \( B_o = B_{v_0v_1} \) and \( B_e = B_{v_0v_2} \) of length \( \ell_o = \lceil \frac{k+1}{2} \rceil \) and \( \ell_e = \lceil \frac{k+1}{2} \rceil \), respectively. Let \( v_1, \ldots, v_k \) denote the remaining trunk vertices of \( C_{d,n} \), enumerated such that \( f_0(v_i) \geq f_0(v_{i+1}) \) for all \( i = 0, \ldots, k - 1 \) and all vertices with odd (even) index belong to \( B_o \) (\( B_e \)). By Lemma 6, \( f_0(v_i) > f_0(v_{i+2}) \) for all \( i = 1, \ldots, k - 2 \). Now we rearrange the vertices of \( G_0 = C_{d,n} \) in a spiral-like way to obtain \( G_1 \):

1. Switch edges \( v_0u_0^3 \) and \( v_1v_3 \) with \( v_0v_3 \) and \( v_1u_0^3 \), where \( u_0^3 \sim v_0 \) is a pendant vertex. By Lemma 4, we obtain a tree \( T_1 \in \mathcal{T}_{d,n} \) and a unimodular function \( g_1 \) on \( T_1 \) with \( \mathcal{R}_{T_1}(g_1) \geq \mathcal{R}_{G_0}(f_0) \).
2. Start with \( S = \{1, 2, 3\} \) and \( R = \{4, 5, \ldots, k\} \).
3. Let \( i \) and \( m \) be the least indices in \( S \) and \( R \), respectively, and \( j \) be the least index in \( S \setminus \{i\} \). Then \( v_j \sim v_m \) and \( g_i(v_i) \geq g_i(v_j) \). Let \( l_1, l_2, \) and \( l_3 \) be the length of the branches \( B_{v_iv_1}, B_{v_iv_2}, \) and \( B_{v_iv_3} \) in \( T_i \).
4. If \( \{l_1, l_2, l_3\} = \{\ell_1, \ell_2, \ell_3\} \), then set \( f_1 = g_i \) and stop.
5. If \( l_b = \ell_1 \) for some \( b \in \{1, 2, 3\} \), then remove the indices of the corresponding vertices from \( S \) and \( R \) and goto Step 3.
6. Switch edges \( v_iv_j^b \) and \( v_jv_m \) with \( v_jv_m \) and \( v_iu_j^b \), where \( u_j^b \sim v_i \) is a pendant vertex. By Lemma 4, we obtain a tree \( T_j \in \mathcal{T}_{d,n} \) and a unimodular function \( g_j \) on \( T_j \) with \( \mathcal{R}_{T_j}(g_j) \geq \mathcal{R}_{T_1}(g_i) \).
7. Replace \( S \leftarrow (S \cup \{m\}) \setminus \{i\} \) and \( R \leftarrow R \setminus \{m\} \) and goto Step 3.

It is straightforward to show that this procedure creates \( G_1 \) and that \( \mathcal{R}_{G_1}(f_1) \geq \mathcal{R}_{G_0}(f_0) \). \( \square \)

All remaining steps in sequence (4) are simpler to handle.

Lemma 8 Let \( G_i \rightarrow G_{i+1} \) be the inverse of a branch reduction in sequence (4) with reduction point \( v^* \), for an \( i = 1, \ldots, t - 1 \). Assume \( f_i \) is a unimodal function on \( G_i \) such that its maximum \( \hat{v} \) is either in \( v^* \) or not contained in the fork of the branch reduction. Then there exists a unimodal function \( f_{i+1} \) in \( G_{i+1} \) with maximum \( \hat{v} \) and \( \mathcal{R}_{G_{i+1}}(f_{i+1}) \geq \mathcal{R}_{G_i}(f_i) \).

**Proof.** The inverse of the branch reduction is performed by switching edges \( v^*u_1^i \) and \( v_2u_2 \) with edges \( v^*u_2 \) and \( v_2u_1^i \), see Fig. 2. From unimodality we can conclude that \( f_i \) restricted to the fork of the branch reduction, \( B_{v^*u_2} \cup B_{v^*x_1} \), attains its maximum in \( v^* \). In particular we have \( f_i(v^*) \geq f_i(v_2) \). Hence the assumptions of Lemma 4 hold and the result follows. \( \square \)
Notice that the condition of Lemma 8 is always satisfied when \( f_i \) attains its maximum in a branching point of \( G_i \).

**Proof of Theorem 2.** Suppose that \( G \) is not a caterpillar. Let \( C_{d,n} = G_0 \rightarrow G_1 \rightarrow \cdots \rightarrow G_{t-1} \rightarrow G_t = G \) be a sequence of inverses of minimal branch reductions. Let \( k \) again denote the number of non-pendant vertices of \( C_{d,n} \). Assume first that the longest branch in \( G_1 \) has length \( \ell \leq \left\lceil \frac{k+1}{2} \right\rceil \). Then by Lemma 7 we can construct a unimodal function \( f_1 \) on \( G_1 \) which attains its maximum in the branching point. By applying Lemma 8 for all remaining inverse branch reductions we get a unimodal function \( f \) on \( G \) with \( R_G(f) \geq \lambda(C_{d,n}) \).

Assume now that there is a proper branch in \( G_1 \) with length \( \ell > \left\lceil \frac{k+1}{2} \right\rceil \). Then the fork of the minimal branch reduction contains less than \( \left\lfloor \frac{k+1}{2} \right\rfloor \) non-pendant vertices and thus \( \hat{v} \) must be contained in the remaining branch of \( G_1 \). Hence by Lemma 8 we get a unimodal function \( f_1 \) on \( G_1 \) where its maximum \( \hat{v} \) is located on the longest proper branch of \( G_1 \). Notice that for all subsequent inverse minimal branch reductions \( G_i \rightarrow G_{i+1} \), each fork must have less than \( \left\lfloor \frac{k+1}{2} \right\rfloor \) non-pendant vertices and thus cannot contain maximum \( \hat{v} \). Therefore we find a unimodal function \( f \) on \( G \) with \( R_G(f) \geq \lambda(C_{d,n}) \) by Lemma 8.

At last we have to note that equality \( R_G(f) = \lambda(C_{d,n}) \) only holds if none of the inequalities in Lemmata 4 and 7 are strict, which implies that \( f_0 \) is constant on \( C_{d,n} \), a contradiction to Lemma 6.

**Remark 9** Theorem 1 can be derived in the same way. Let \( \mu(G) \) denote the largest eigenvalue of \( A(G) \). Then we can use the Perron-Frobenius Theorem, the corresponding eigenvalue equation \( \mu f(v) = \sum_{uv \in E} f(u) \), Rayleigh quotient \( A_G(f) = \langle Af, f \rangle = 2 \sum_{uv \in E} f(u)f(v) \) for a vector \( ||f|| = 1 \), and the fact that \( \mu(G) > 1 \) if \( G \neq K_1, K_2 \), to verify the analogous versions of Lemmata 4 and 6. We have worked out the details in a technical report [3].

3 Non-semiregular trees

Let \( T_\pi \) denote the class of trees with degree sequence \( \pi \). Then we can again ask for the structure of trees with minimal spectral radius in \( T_\pi \). The naive conjecture states: If a tree \( G \) has minimal spectral radius in class \( T_\pi \), then \( G \) is a caterpillar. Unfortunately, computational experiments have shown that this conjecture is false. We performed an exhaustive search on trees on up to 20 vertices using Wolfram’s Mathematica and Royle’s Combinatorial Catalogues [10] and found several counter examples. Figure 3 shows some of the trees with the same minimal index among all trees with the same degree sequence. The tree on the left hand side is also extremal with respect to the Laplacian.
spectral radius.

Fig. 3. Three of the extremal trees with degree sequence $\pi = (4^4, 3^2, 2, 1^{12})$; all have spectral radius (index) $\mu(G) = \sqrt{6}$.

Unfortunately we were not able to detect a general pattern. Our observations for the the adjacency and the Laplacian matrix could be summarized in the following way:

- Extremal trees need not be unique (up to isomorphism). Figure 3 gives an example.
- None of the extremal trees has to be a caterpillar.
- Buds have largest degree in each proper branch of an extremal tree.
- Degrees need not be monotone along the trunk of a proper branch.

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References


