EULER MATRICES OF QUIVERS AND MAHLER MEASURE

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ABSTRACT. For a given quiver Q, we can define the matrix B such that $B = -(E^T)E^{-1}$, where E is the Euler matrix of Q. We investigate the roots of the characteristic polynomial of B for small quivers, including the simply laced Dynkin diagrams. We show that the characteristic polynomial of B is reciprocal and that its roots must lie on the unit circle in the complex plane when $E+E^T$ is positive definite. For this project, we consulted with Professor Harm Derksen.

1. INTRODUCTION

We investigate the properties of the characteristic polynomial for a matrix B defined on a quiver. We are interested in the roots of this characteristic polynomial and where they lie in the complex plane.

We begin by providing basic definitions of quivers, the Euler matrix E associated to a quiver. We then demonstrate several basic facts about quivers and their Euler matrices. In section 2 we consider the form of the characteristic polynomials of B, and show that they are self-reciprocal polynomials. In section 3, we consider how properties of $E+E^T$ affect the roots of $\det(\lambda I - B)$. We show that when $E+E^T$ is positive definite, the roots of B must lie on the unit circle in the complex plane. In section 4, we provide an example to motivate further exploration of the relationship between the associated polynomial of a quiver and the associated polynomials of its subquivers. We conjecture that the Mahler measure of a subquiver must be smaller than the Mahler measure of the whole quiver.

1.1. History.

One way to look at the roots of a polynomial is to consider its *Mahler measure*, defined as

$$M(P) = |a_d|\Pi_{k=1}^n \max\{1, |\alpha_k|\}$$

Where

$$P(\lambda) = a_n\Pi_{k=1}^n(\lambda - \alpha_k)$$

has integer coefficients; see [6].

It is not known if there is some $P(x)$ with $M(P) = 1+\epsilon$ for $\epsilon > 0$. This question is referred to as *Lehmer's Conjecture* or *Lehmer's Question* [6]:

Question 1.1. *Does there exist some $C > 1$ such that for every polynomial $P(x) \in \mathbb{Z}[x]$, $M(P) = 1$ or $M(P) > C$?*

Lehmer conjectured that $C \approx 1.1762808$, given by $M(P)$ for

$$P(\lambda) = \lambda^{10} + \lambda^9 - \lambda^7 - \lambda^6 - \lambda^5 - \lambda^4 - \lambda^3 + \lambda + 1$$

see [6].

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Lehmer first introduced his question in the 1933 paper *Factorization of Certain Cyclotomic Functions* [5]. The initial paper was motivated by an approach for finding large primes [4]. A lemma of Kronecker implies that if $M(P) = 1$, then P is a product of powers of λ and cyclotomic polynomials; see [4].

Some partial results bounding Mahler measure have been established. Breusch proved in 1951 that a monic, irreducible, and nonreciprocal polynomial P then

$$M(P) \geq 1.324717\ldots$$

which is the real root of $\lambda^3 - \lambda - 1$ [4]. Later, in 1979, Dobrowolski showed that for a monic, irreducible, and non-cyclotomic P,

$$M(P) > 1 + c\left(\frac{\log\log d}{\log d}\right)^3$$

for some constant c; see [4].

Several computational searches have been carried out in addition to the above approaches. None have yielded a counterexample to Lehmer's question [6]. Mossinghoff carried out a search for all polynomials of degree at most 24 with Mahler measure less than 1.3; while the specific algorithm used applied only to even degrees, he was able to find 48 such polynomials of degree 22 and 46 of degree 24 [6]. He was additionally able to use several other algorithms to extend the search calculations to more degrees, and was able to find a limit point for measures near 1.309; see [6].

For more information on the work around Lehmer's question, see the cited works *Mahler Measure of Polynomials* [4] and *Polynomials with Small Mahler Measure* [6].

We now introduce basic terminology that motivates our approach to the problem, before providing some background into the project motivations. The main objects under study are quivers, and the related matrices are defined for use in the theory of quiver representations.

1.2. **Quivers.**

Definition 1. [3] A *quiver* Q is a 4-tuple $Q = (Q_0, Q_1, h, t)$ where Q_0 is a finite set of vertices, Q_1 is the set of edges, and $h : Q_1 \to Q_0$ and $t : Q_1 \to Q_0$ are functions that give the head and tail of each edge, respectively.

Definition 2. [3] A *path* on a quiver $Q = (Q_0, Q_1, h, t)$ from u to v for $u, v \in Q_0$ is some sequence of edges $e_0, \ldots, e_n$ such that for all $0 \leq i \leq n$, $h(e_{i-1}) = t(e_i)$ and $t(e_0) = u$, $h(e_n) = v$.

Examples 1.2. Consider the following simple quivers:

(1) Consider the quiver illustrated by the following diagram:

$$\begin{tikzcd} 1 \arrow[r] & 2 \arrow[r] & 3 \arrow[r] & 4 \end{tikzcd}$$

Then $Q_0 = \{1, 2, 3, 4\}$, $Q_1 = \{(1, 2), (2, 3), (3, 4)\}$, and $h((1, 2)) = 2$ while $t((1, 2)) = 1$.

(2) Consider

$$\begin{tikzcd} 1 \arrow[loop above] \arrow[r, bend left] & 2 \arrow[l, bend left] \end{tikzcd}$$

Then $Q_0 = \{1, 2\}$, $Q_1 = \{(1, 2), (2, 1), (1, 1)\}$, and $h((1, 1)) = t((1, 1)) = 1$.

Notice that self-loops and cycles are permitted, and that the functions h and t are not necessarily injective, i.e. edges with the same head and tail may be repeated. However, we will be considering quivers that do not contain *oriented cycles*:

Definition 3. [3] An *oriented cycle* of a quiver $Q = (Q_0, Q_1, h, t)$ is a path from some $u \in Q_0$ to u.

Example 1.3. Consider again the quivers in Examples 1.2. Observe that the first quiver does not contain an oriented cycle, as there is no path from any node back to itself. However, the second quiver contains multiple oriented cycles; one consists only of the self-loop on 1, while the other consists of the edges $(1, 2)$ and $(2, 1)$.

1.3. **Quiver Representations.** The matrices under study for this project are used in the study of quiver representations; however, the definitions are in terms of quivers and not quiver representations. In particular, we use the *Euler matrix* of a quiver:

Definition 4. [3] Given a quiver $Q = (Q_0, Q_1, h, t)$, then the *Euler matrix* E of Q is defined as

$$E_{i,j} = \delta_{i,j} - |\{a \in Q_1 : t(a) = i, h(a) = j\}|$$

where $\delta_{i,j}$ is the Kronecker symbol, defined as

$$\delta_{i,j} = \begin{cases} 1 \text{ if } i = j \\ 0 \text{ if } i \neq j \end{cases}$$

Definition 5. We define the *Auslander-Reiter Matrix* B of an acyclic quiver Q to be $B = -E^T E^{-1}$ where E is the Euler matrix of Q. This matrix is used in the Auslander-Reiter transform in the theory of quiver representations; see [3]. However, defining that transform is beyond the scope of this project.

An important note is that E is singular when its defining quiver is cyclic [2]; this is why we restrict our definition of B to acyclic quivers Q.

1.4. **Topological Ordering.** Importantly, we know that any directed acyclic graph has a *topological ordering* of vertices; see [7], wherein any edge e of a quiver $Q = \{Q_0, Q_1, h, t\}$ has $h(e) \geq t(e)$. We can visualize these orderings by drawing the vertices in a line from least to greatest and adding edges accordingly.

Example 1.4. Consider the quiver A_3 as illustrated below:

$$\begin{tikzcd} 1 \arrow[r] & 2 & 3 \arrow[l] \end{tikzcd}$$

We may construct a topological ordering of this graph by re-numbering vertex 3 as vertex 2. We can then draw the graph like this:

$$\begin{tikzcd} 1 \arrow[rr, bend right] & 2 \arrow[r] & 3 \end{tikzcd}$$

Notice that now the edges all flow in the same direction. If we consider the example as an acyclic quiver, we see that arranging the vertices in a topological order means that E will be an upper triangular matrix; in particular, for this quiver A_3,

$$E = \begin{pmatrix} 1 & 0 & -1 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix}.$$

And this can similarly be done with a reversed ordering of the vertices to obtain a lower triangular E. It follows from the definitions that any topological ordering of a quiver will lead to E being triangular. Therefore, we will use this fact to assume that E is defined as a triangular matrix with diagonal values of 1 when we use it in examples and calculations. According to professor Derksen, if such an ordering can be constructed, it will not change the eigenvalues of B [2].

Proposition 1.5. *Let E be an Euler matrix of an acyclic quiver written in triangular form. Then (a) $\det(E) = 1$, and (b) $\det(\lambda I - B) = \det(\lambda E + E^T)$*

Proof. (a) Since E is defined on an acyclic quiver, there are no edges (i, i) for any vertex i. Therefore $E_{i,i} = \delta_{i,i} - 0 = 1$. Since E is triangular by assumption and has diagonal entries 1, $\det(E) = 1$. □

Proof. (b) Consider

$$\begin{aligned}\det((\lambda I - B)E) &= \det(\lambda I - B)\det(E)\\ &= \det((\lambda + E^T E^{-1})E)\\ &= \det(\lambda E + E^T)\end{aligned}$$

Since by (a), $\det(E) = 1$, we see that

$$\det((\lambda I - B)E) = \det(\lambda I - B) = \det(\lambda E + E^T)$$

□

2. The Characteristic Polynomial of $B = -E^T E^{-1}$

For this section, we assume that E is the Euler matrix of some acyclic quiver, with the vertices of that quiver numbered such that E is upper or lower triangular. We consider the form of the characteristic polynomial of $B = -E^T E^{-1}$, and ask the following question:

Question 2.1. *Which polynomials P can be written as $P(\lambda) = \det(\lambda I - B)$?*

Via inspection of examples, we observed that the coefficients of $\det(\lambda I - B)$ appeared to be palindromic; that is, reversing the order of the coefficients yields the same polynomial. We formalize this with the notion of a *self-reciprocal polynomial*, which is some polynomial $P(\lambda)$ such that

$$\begin{aligned}P(\lambda) &= a_n\lambda^n + a_{n-1}\lambda^{n-1} \cdots + a_i\lambda^i + \cdots + a_1\lambda + a_0\\ &= a_0\lambda^n + a_1\lambda^{n-1} + \cdots + a_{n-i}\lambda^i + \cdots + a_{n-1}\lambda + a_n\end{aligned}$$

where $a_n \neq 0, a_0 \neq 0$; see [9].

Proposition 2.2. *Let $B = -E^T E^{-1}$ where E is an $n \times n$ triangular Euler matrix of an acyclic quiver. Then $\det(\lambda I - B)$ is self-reciprocal.*

Proof. Let $P(\lambda) = \det(\lambda I - B)$. Then by proposition 1.5,

$$P(\lambda) = \det(\lambda E + E^T) = \det(E + \lambda E^T)$$

Considering $P(\lambda)$ in the ring of Laurent polynomials $\mathbb{R}[\lambda, \lambda^{-1}]$ we can say that

$$P(\lambda) = \det(\lambda E + E^T) = \lambda^n \det\left(E + \frac{1}{\lambda}E^T\right) = \lambda^n P\left(\frac{1}{\lambda}\right)$$

Therefore by comparing coefficients we find that P is self-reciprocal. □

Remark 2.3. Notice that here we are factoring out an indeterminate λ, and we obtain the equation $P(\lambda) = \lambda^N P\left(\frac{1}{\lambda}\right)$. This equation is equivalent to $P \in \mathbb{R}[\lambda]$ being a self-reciprocal polynomial; see [9]. But for indeterminate λ this means that we are considering $P(\lambda)$ and $P\left(\frac{1}{\lambda}\right)$ as elements of the ring of Laurent polynomials $\mathbb{R}[\lambda, \lambda^{-1}]$, rather than the usual $\mathbb{R}[\lambda]$. In the literature that we have encountered, this seems to be left implicit when the equality $P(\lambda) = \lambda^n P\left(\frac{1}{\lambda}\right)$ is written.

Example 2.4. Consider the characteristic polynomials of $B = -E^T E^{-1}$ for the quivers below.

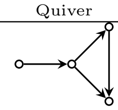
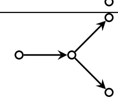
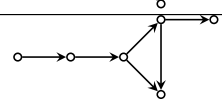
Quiver	$\det(\lambda I - B)$
	$\lambda^4 - \lambda^3 - 3\lambda^2 - \lambda + 1$
	$\lambda^4 + \lambda^3 + \lambda^2 + \lambda + 1$
	$\lambda^6 - \lambda^5 - 5\lambda^4 - 7\lambda^3 - 5\lambda^2 - \lambda + 1$

Table 1: Several quivers, and the characteristic polynomial of the associated $B = -E^T E^{-1}$

Notice that the coefficients of each polynomial are palindromic, as proven above. Further research could find more specific restrictions on $\det(\lambda I - B)$; perhaps the coefficients must have other properties in addition to being palindromic.

3. Eigenvalues of B when $E + E^T$ is positive definite

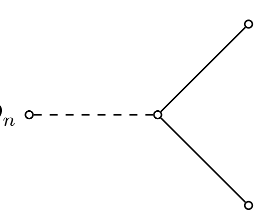
Let $B = -E^T E^{-1}$ where E is the Euler matrix of some acyclic quiver written in triangular form. For certain quivers, representation theory can tell us about the properties of B and and E; in particular, the quivers known as the simply laced Dynkin diagrams are well-studied, as they have connections to many other topics.

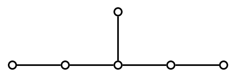
We consider the following question:

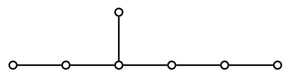
Question 3.1. *Given a triangular matrix E of some acyclic quiver, is it the case that if $E + E^T$ is positive definite, then the eigenvalues of B are on the unit circle in the complex plane?*

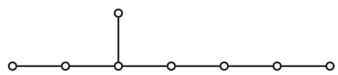
The property of $E + E^T$ being positive definite corresponds to the associated quiver having an underlying graph that is one of the *simply laced Dynkin diagrams*, denoted A_n, D_n, E_6, E_7, and E_8; see [3]. We present the simply laced Dynkin diagrams below:

A_n

D_n 

E_6 

E_7 

E_8 

We present the Euler matrices for each of these quivers, along with the product $B = -E^T E^{-1}$ and $\det(\lambda I - B)$ along with a graph of its roots below.

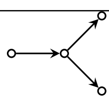
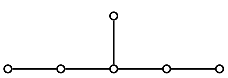
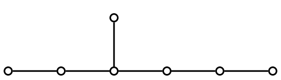
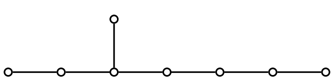
Quiver	E	$B = -E^T E^{-1}$
A_4	$E = \begin{pmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	$B = \begin{pmatrix} -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$
D_4 	$E = \begin{pmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	$B \begin{pmatrix} -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$
E_6 	$E = \begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$B = \begin{pmatrix} -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$
E_7 	$E + \begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$B = \begin{pmatrix} -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$
E_8 	$E = \begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$B = \begin{pmatrix} -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$

Table 2: Simply laced Dynkin diagrams, their Euler matrices, and product B

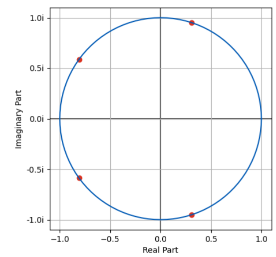
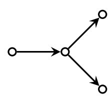
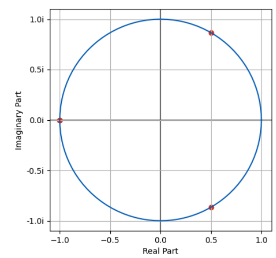
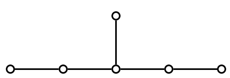
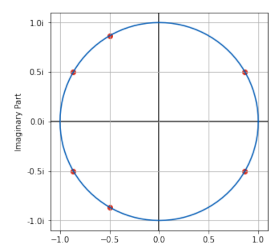
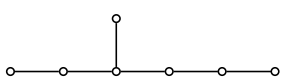
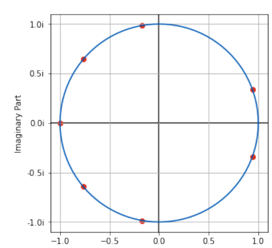
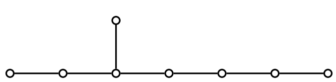
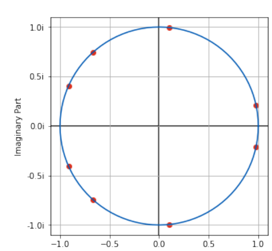
Quiver	$\det(\lambda I - B)$	Roots of $\det(\lambda I - B)$
A_4	$\lambda^4 + \lambda^3 + \lambda^2 + \lambda + 1$	
D_4 	$\lambda^4 + \lambda^3 + \lambda + 1$	
E_6 	$\lambda^6 + \lambda^5 - \lambda^3 + \lambda + 1$	
E_7 	$\lambda^7 + \lambda^6 - \lambda^4 - \lambda^3 + \lambda + 1$	
E_8 	$\lambda^8 + \lambda^7 - \lambda^5 - \lambda^4 - \lambda^3 + \lambda + 1$	

Table 3: Simply laced Dynkin diagrams, $\det(\lambda I - B)$, and graph of its roots

We observe that the roots of $\det(\lambda I - B)$ for these diagrams are all on the unit circle. We also observe that $E + E^T$ is positive definite when the quiver used to define E is a simply laced Dynkin diagram [2]. The next result shows that these two facts are related.

Proposition 3.2. *Suppose an acyclic quiver has a triangular Euler matrix E and that $E + E^T$ is positive definite. Let $B = -E^T E^{-1}$. Then the roots of* $\det(\lambda I - B)$ *lie on the unit circle in the complex plane.*

Proof. Let x be an eigenvalue of B. Then by proposition 1.5, x is a root of $\det(\lambda E + E^T)$. Since $\det(xE+E^T) = 0$, $\ker(xE+E^T) \neq \{0\}$. Choose some $\mathbf{v} \in \ker(xE+E^T)$. Then $0 = (xE + E^T)\mathbf{v} = xE\mathbf{v} + E^T\mathbf{v}$ and therefore

$$xE\mathbf{v} = -E^T\mathbf{v} \tag{1}$$

Taking the conjugate transpose of both sides, we see that

$$\begin{aligned} \mathbf{v}^* E &= -\bar{x}\mathbf{v}^* E^T, \text{ so} \\ \mathbf{v}^* E\mathbf{v} &= -\bar{x}\mathbf{v}^* E^T\mathbf{v} \text{ by } (1) \\ &= \bar{x}\mathbf{v}^*(xE\mathbf{v}) \\ &= |x|\mathbf{v}^* E\mathbf{v} \end{aligned} \tag{2}$$

Assume for the sake of contradiction that

$$\mathbf{v}^* E\mathbf{v} = 0 \tag{3}$$

By taking the conjugate transpose we find that

$$\mathbf{v}^* E^T\mathbf{v} = 0 \tag{4}$$

Adding together (3) and (4), we find that $\mathbf{v}^*(E + E^T)\mathbf{v} = 0$; however, this contradicts that $E + E^T$ is positive definite. Then, by (2) we obtain $|x|^2 = 1$, so we conclude that $|x| = 1$. $\square$

The converse is not true; consider the following example:

Example 3.3. Consider the quiver $\hat{A}_3$

$$\begin{tikzcd} & 2 \arrow[d] \\ 1 \arrow[ur] \arrow[dr] & \\ & 3 \end{tikzcd}$$

Then

$$E = \begin{pmatrix} 1 & -1 & -1 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{pmatrix}$$

and so

$$E + E^T = \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}$$

But then $E + E^T$ has 0 as an eigenvalue, and so it is not positive definite. However, the roots of $B = -E^T E^{-1}$ for this quiver are ± 1, which do lie on the unit circle. Further research could investigate what properties $E + E^T$ should have such that the roots of $\det(xI - B)$ are on the unit circle.

4. Roots of Subquivers

In this section, we again consider $B = -E^T E^{-1}$ for some triangular Euler matrix E for an acyclic quiver. Consider the following example, created by repeateddly adding a single vertex and edge to a small quiver:

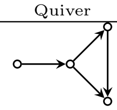
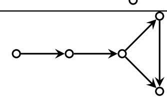
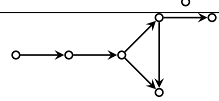
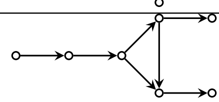
Quiver	$\det(\lambda I - B)$	$M(\det(\lambda I - B))$
	$\lambda^4 - \lambda^3 - 3\lambda^2 - \lambda + 1$	2.3692054071
	$\lambda^5 - \lambda^4 - 3\lambda^3 - 3\lambda^2 - \lambda + 1$	2.618033988770564
	$\lambda^6 - \lambda^5 - 5\lambda^4 - 7\lambda^3 - 5\lambda^2 - \lambda + 1$	3.3014904324145147
	$\lambda^7 - \lambda^6 - 7\lambda^5 - 13\lambda^4 - 13\lambda^3 - 7\lambda^2 - \lambda + 1$	3.899908930943441

Table 4: "Pendulum" quiver sequence and characteristic polynomials of B

Here, $M(\det(\lambda I - B))$ refers to the *Mahler measure* [6] of the characteristic polynomial of B. Notice that the Mahler measure of each quiver is increasing as more edges and vertices are added. We conjecture that this must be the case:

Conjecture 4.1. Let $Q' \subset Q$ be acyclic quivers with Euler matrices $E_{Q'}$ and E_Q, respectively. Let $B_{Q'} = -E^T_{Q'} E^{-1}_{Q'}$ and $B_Q = -E^T_Q E^{-1}_Q$. Then

$$M(\det(\lambda I - B_{Q'}) \leq M(\det(\lambda I - B_Q)$$

Future work could prove or disprove this conjecture.

Appendix A. Source Code

The source code used to generate examples, graphs, and calculations can be found at https://github.com/nichols-t/f20-math4020-quiver-matrices.

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