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THE IMAGES OF NON-COMMUTATIVE POLYNOMIALS EVALUATED ON 2×2 MATRICES

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ABSTRACT. Let p be a multilinear polynomial in several non-commuting variables with coefficients in a quadratically closed field K of any characteristic. It has been conjectured that for any n, the image of p evaluated on the set $M_n(K)$ of n by n matrices is either zero, or the set of scalar matrices, or the set $sl_n(K)$ of matrices of trace 0, or all of $M_n(K)$. We prove the conjecture for $n = 2$, and show that although the analogous assertion fails for completely homogeneous polynomials, one can salvage the conjecture in this case by including the set of all non-nilpotent matrices of trace zero and also permitting dense subsets of $M_n(K)$.

1. INTRODUCTION

Images of polynomials evaluated on algebras play an important role in non-commutative algebra. In particular, various important problems related to the theory of polynomial identities have been settled after the construction of central polynomials by Formanek [F1] and Razmyslov [Ra1].

The parallel topic in group theory (the images of words in groups) also has been studied extensively, particularly in recent years. Investigation of the image sets of words in pro-p-groups is related to the investigation of Lie polynomials and helped Zelmanov [Ze] to prove that the free pro-p-group cannot be embedded in the algebra of $n \times n$ matrices when $p \gg n$. (For $p > 2$, the impossibility of embedding the free pro-p-group into the algebra of 2×2 matrices had been proved by Zubkov [Zu].) The general problem of non-linearity of the free pro-p-group is related on the one hand with images of Lie polynomials and words in groups, and on the other hand with problems of Specht type, which is of significant current interest.

Borel [Bo] (also cf. [La]) proved that for any simple (semisimple) algebraic group G and any word w of the free group on r variables, the word map $w : G^r \to G$ is dominant. Larsen and Shalev [LaS] showed that any element of a simple group can be written as a product of length two in the word map, and Shalev [S] proved Ore's conjecture, that the image of the commutator word in a simple group is all of the group.

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In this paper we consider the question, reputedly raised by Kaplansky, of the possible image set Im p of a polynomial p on matrices. When $p = x_1x_2 - x_2x_1$, this is a theorem of Albert and Muckenhoupt [AlM]. For an arbitrary polynomial, the question was settled for the case when K is a finite field by Chuang [Ch], who proved that a subset $S \subseteq M_n(K)$ containing 0 is the image of a polynomial with constant term zero if and only if S is invariant under conjugation. Later Chuang's result was generalized by Kulyamin [Ku1], [Ku2] for graded algebras.

Chuang [Ch] also observed that for an infinite field K, if Im p consists only of nilpotent matrices, then p is a polynomial identity (PI). This can be seen via Amitsur's Theorem [Row, Theorem 3.26, p. 176] that says that the relatively free algebra of generic matrices is a domain. Indeed, p^n must be a PI for $M_n(K)$, implying p is a PI.

Lee and Zhou proved [LeZh, Theorem 2.4] that when K is an infinite division ring, for any non-identity p with coefficients in the center of K, Im p contains an invertible matrix.

Over an infinite field, it is not difficult to ascertain the linear span of the values of any polynomial. Indeed, standard multilinearization techniques enable one to reduce to the case where the polynomial p is multilinear, in which case the linear span of its values comprise a Lie ideal since, as is well known,

$$[a, p(a_1, \dots, a_n)] = p([a, a_1], a_2, \dots, a_n) + p(a_1, [a, a_2], \dots, a_n) + \cdots + p(a_1, \dots, [a, a_n]),$$

and Herstein [Her] characterized Lie ideals of a simple ring R as either being contained in the center or containing the commutator Lie ideal $[R, R]$. Another proof is given in [BK]; also see Lemma 5 below. It is considerably more difficult to determine the actual image set Im p, rather than its linear span.

Thus, in [Dn], Lvov formulated Kaplansky's question as follows:

Question 1 (I. Lvov)**.** Let p be a multilinear polynomial over a field K. Is the set of values of p on the matrix algebra $M_n(K)$ a vector space?

In view of the above discussion, Question 1 is equivalent to the following:

Conjecture 1. *If p is a multilinear polynomial evaluated on the matrix ring $M_n(K)$, then* Im p *is either $\{0\}$, K, $sl_n(K)$, or $M_n(K)$. Here K is the set of scalar matrices and $sl_n(K)$ is the set of matrices of trace zero.*

Example 1. Im p can indeed equal $\{0\}$, K, $sl_n(K)$, or $M_n(K)$. For example, if our polynomial is in one variable and $p(x) = x$, then Im $p = M_n(K)$. The image of the polynomial $[x_1, x_2]$ is $sl_n(K)$. If the polynomial p is central, then its image is K and examples of such polynomials can be found in [Ra1] and in [F1]. Finally if the polynomial p is a PI, then its image is $\{0\}$, and s_{2n} is an example of such a polynomial.

As noted above, the conjecture fails for non-multilinear polynomials when K is a finite field. The situation is considerably subtler for images of non-multilinear, completely homogeneous polynomials than for multilinear polynomials. Over any field K, applying the structure theory of division rings to Amitsur's theorem, it is not difficult to get an example of a completely homogeneous polynomial f, non-central on $M_3(K)$, whose values all have third powers central; clearly its image does not comprise a subspace of $M_3(K)$. Furthermore, in the (non-multilinear) completely homogeneous case, the set of values could be dense without including all matrices. (Analogously, although the finite basis problem for multilinear identities is not yet settled in non-zero characteristic, there are counterexamples for completely homogeneous polynomials; cf. [B].)

Our main results in this paper are for $n = 2$, for which we settle Conjecture 1, proving the following results (see §2 for terminology). We call a field K *quadratically closed* if every non-constant polynomial of degree $\leq 2\deg p$ in $K[x]$ has a root in K.

Theorem 1. *Let $p(x_1, \dots, x_m)$ be a semi-homogeneous polynomial (defined below) evaluated on the algebra $M_2(K)$ of 2×2 matrices over a quadratically closed field. Then* $\operatorname{Im} p$ *is either* $\{0\}$*,* K*, the set of all non-nilpotent matrices having trace zero,* $sl_2(K)$*, or a dense subset of* $M_2(K)$ *(with respect to Zariski topology).*

(We also give examples to show how p can have these images.)

Theorem 2. *If p is a multilinear polynomial evaluated on the matrix ring $M_2(K)$ (where K is a quadratically closed field), then* $\operatorname{Im} p$ *is either* $\{0\}$*,* K*,* sl_2*, or* $M_2(K)$*.*

Whereas for 2×2 matrices one has a full positive answer for multilinear polynomials, the situation is ambiguous for homogeneous polynomials, since, as we shall see, certain invariant sets cannot occur as their images. For the general non-homogeneous case, the image of a polynomial need not be dense, even if it is non-central and takes on values of non-zero trace, as we see in Example 5. In this paper, we start with the homogeneous case (which includes the completely homogeneous case, then discuss the non-homogeneous case, and finally give the complete picture for the multilinear case.

The proofs of our theorems use some algebraic-geometric tools in conjunction with ideas from graph theory. The final part of the proof of Theorem 2 uses the First Fundamental Theorem of Invariant Theory (that in the case Char $K = 0$, invariant functions evaluated on matrices are polynomials involving traces), proved by Helling [Hel], Procesi [P], and Razmyslov [Ra3]. The formulation in positive characteristic, due to Donkin [D], is somewhat more intricate. $\mathrm{GL}_n(K)$ acts on $m-$tuples of $n \times n$ matrices by simultaneous conjugation.

Theorem (Donkin [D])**.** *For any $m, n \in \mathbb{N}$, the algebra of polynomial invariants $K[M_n(K)^m]^{\mathrm{GL}_n(K)}$ under $\mathrm{GL}_n(K)$ is generated by the trace functions*

$$T_{i,j}(x_1, x_2, \dots, x_m) = \mathrm{Trace}(x_{i_1} x_{i_2} \cdots x_{i_r}, \bigwedge^j K^n), \tag{1}$$

where $i = (i_1, \dots, i_r)$, all $i_l \leq m$, $r \in \mathbb{N}, j > 0$, and $x_{i_1} x_{i_2} \cdots x_{i_r}$ acts as a linear transformation on the exterior algebra $\bigwedge^j K^n$.

Remark. For $n = 2$ we have a polynomial function in expressions of the form $\mathrm{Trace}(A, \bigwedge^2 K^2)$ and $\mathrm{tr} A$ where A is monomial. Note that $\mathrm{Trace}(A, \bigwedge^2 K^2) = \det A$.

(The Second Fundamental Theorem, dealing with relations between invariants, was proved by Procesi [P] and Razmyslov [Ra3] in the case Char $K = 0$ and by Zubkov [Zu] in the case Char $K > 0$.)

Other works on polynomial maps evaluated on matrix algebras include [W], [GK], who investigated maps that preserve zeros of multilinear polynomials.

2. Definitions and basic preliminaries

By $K\langle x_1,\dots,x_m\rangle$ we denote the free K-algebra generated by non-commuting variables $x_1,\dots,x_m$, and refer to the elements of $K\langle x_1,\dots,x_m\rangle$ as *polynomials.* Consider any algebra R over a field K. A polynomial $p\in K\langle x_1,\dots,x_m\rangle$ is called a *polynomial identity* (PI) of the algebra R if $p(a_1,\dots,a_m)=0$ for all $a_1,\dots,a_m\in R$; $p\in K\langle x_1,\dots,x_m\rangle$ is a *central polynomial* of R if for any $a_1,\dots,a_m\in R$ one has $p(a_1,\dots,a_m)\in \mathrm{Cent}(R)$ but p is not a PI of R. A polynomial p (written as a sum of monomials) is called *semi-homogeneous of weighted degree* d with (integer) *weights* $(w_1,\dots,w_m)$ if for each monomial h of p, taking d_j to be the degree of x_j in p, we have

$$d_1w_1+\cdots+d_nw_n=d.$$

A semi-homogeneous polynomial with weights $(1,1,\dots,1)$ is called *homogeneous* of degree d.

A polynomial p is *completely homogeneous* of multidegree $(d_1,\dots,d_m)$ if each variable x_i appears the same number of times d_i in all monomials. A polynomial $p\in K\langle x_1,\dots,x_m\rangle$ is called *multilinear* of degree m if it is linear (i.e., homogeneous of multidegree $(1,1,\dots,1)$). Thus, a polynomial is multilinear if it is a polynomial of the form

$$p(x_1,\dots,x_m)=\sum_{\sigma\in S_m} c_\sigma x_{\sigma(1)}\cdots x_{\sigma(m)},$$

where S_m is the symmetric group in m letters and the coefficients c_σ are constants in K.

We need a slight modification of Amitsur's theorem, which is well known:

Proposition 1. *The algebra of generic matrices with traces is a domain which can be embedded in the division algebra UD of central fractions of Amitsur's algebra of generic matrices. Likewise, all of the functions in Donkin's theorem can be embedded in UD.*

Proof. Any trace function can be expressed as the ratio of two central polynomials, in view of [Row, Theorem 1.4.12]; also see [BR, Theorem J, p. 27], which says for any characteristic coefficient α_k of the characteristic polynomial $\lambda^t+\sum_{k=1}^t(-1)^k\alpha_k\lambda^{t-k}$ that

$$\alpha_k f(a_1,\dots,a_t,r_1,\dots,r_m)=\sum_{k=1}^t f(T^{k_1}a_1,\dots,T^{k_t}a_t,r_1,\dots,r_m), \tag{2}$$

summed over all vectors $(k_1,\dots,k_t)$ where each $k_i\in\{0,1\}$ and $\sum k_i=t$, where f is any $t-$alternating polynomial (and $t=n^2$). In particular,

(3)

$$\mathrm{tr}(T)f(a_1,\dots,a_t,r_1,\dots,r_m)=\sum_{k=1}^t f(a_1,\dots,a_{k-1},Ta_k,a_{k+1},\dots,a_t,r_1,\dots,r_m),$$

so any trace of a polynomial belongs to UD. In general, the function (1) of Donkin's theorem can be written as a characteristic equation, so we can apply Equation (2). □

Here is one of the main tools for our investigation.

Definition 1. A *cone* of $M_n(K)$ is a subset closed under multiplication by non-zero constants. An *invariant cone* is a cone invariant under conjugation. An invariant cone is *irreducible* if it does not contain any non-empty invariant cone.

Example 2. Examples of invariant cones of $M_n(K)$ include:

(i) The set of diagonalizable matrices.
(ii) The set of non-diagonalizable matrices.
(iii) The set K of scalar matrices.
(iv) The set of nilpotent matrices.
(v) The set sl_n of matrices having trace zero.

3. Images of polynomials

For any polynomial $p \in K\langle x_1, \dots, x_m\rangle$, the *image* of p (in R) is defined as

$$\text{Im } p = \{A \in R : \text{ there exist } a_1, \dots, a_m \in R \text{ such that } p(a_1, \dots, a_m) = A\}.$$

Remark 1. Im p is invariant under conjugation, since

$$\alpha p(x_1, \dots, x_m)\alpha^{-1} = p(\alpha x_1\alpha^{-1}, \alpha x_2\alpha^{-1}, \dots, \alpha x_m\alpha^{-1}) \in \text{Im } p,$$

for any non-singular $\alpha \in M_n(K)$.

Lemma 1. *If* Char K *does not divide* n*, then any non-identity* $p(x_1, \dots, x_m)$ *of* $M_n(K)$ *must either be a central polynomial or take on a value which is a matrix whose eigenvalues are not all the same.*

Proof. Otherwise $p(x_1, \dots, x_m) - \frac{1}{n}\text{tr}(p(x_1, \dots, x_m))$ is a nilpotent element in the algebra of generic matrices with traces, so by Proposition 1 is 0, implying p is central. □

Let us continue with the following easy but crucial lemma.

Lemma 2. *Suppose the field* K *is closed under* d*-roots. If the image of a semi-homogeneous polynomial* p *of weighted degree* d *intersects an irreducible invariant cone* C *non-trivially, then* $C \subseteq \text{Im } p$.

Proof. If $A \in \text{Im } p$, then $A = p(x_1, \dots, x_m)$ for some $x_i \in M_n(K)$. Thus for any $c \in K$, $cA = p(c^{w_1/d}x_1, c^{w_2/d}x_2, \dots, c^{i_m/d}x_m) \in \text{Im } p$, where $(w_1, \dots, w_m)$ are the weights. This shows that Im p is a cone. □

Remark 2. When the polynomial p is multilinear, we take the weights $w_1 = 1$ and $w_i = 0$ for all $i > 1$, and thus do not need any assumption on K to show that the image of any multilinear polynomial is an invariant cone.

Lemma 3. *If* Im p *consists only of diagonal matrices, then the image* Im p *is either* $\{0\}$ *or the set* K *of scalar matrices.*

Proof. Suppose that some non-scalar diagonal matrix $A = \text{Diag}\{\lambda_1, \dots, \lambda_n\}$ is in the image. Therefore $\lambda_i \neq \lambda_j$ for some i and j. The matrix $A' = A + e_{ij}$ (here e_{ij} is the matrix unit) is conjugate to A, so by Remark 1 also belongs to Im p. However A' is not diagonal, a contradiction. □

Lemma 4. *Assume that the* x_i *are matrix units. Then* $p(x_1, \dots, x_m)$ *is either* 0 *or* $c \cdot e_{ij}$ *for some* $i \neq j$ *or a diagonal matrix.*

Proof. Suppose that the x_i are matrix units e_{k_i,l_i}. Then the product $x_1 \cdots x_m$ is non-zero if and only if $l_i = k_{i+1}$ for each i, and in this case this product is equal to e_{k_1,l_m}. If the x_i are such that there is at least one $\sigma \in S_n$ such that $x_{\sigma(1)} \cdots x_{\sigma(m)}$ is non-zero, then we can consider a graph on n vertices whereby we connect vertex i with vertex j by an oriented edge if there is a matrix e_{ij} in our set $\{x_1, x_2, \dots, x_m\}$. It can happen that we will have more than one edge that connects i to j, and it is also possible that we will have edges connecting a vertex to itself. The evaluation $p(x_1, \dots, x_m) \neq 0$ only if there exists an Eulerian cycle or an Eulerian path in the graph. This condition is necessary but is not sufficient. From graph theory we know that there exists an Eulerian path only if the degrees of all vertices but two are even, and the degrees of these two vertices are odd. Also we know that there exists an Eulerian cycle only if the degrees of all vertices are even. Thus when $p(x_1, \dots, x_m) \neq 0$, there exists either an Eulerian path or an Eulerian cycle in the graph. In the first case we have exactly two vertices of odd degree such that one of them (i) has more output edges and another (j) has more input edges. Thus the only non-zero terms in the sum of our polynomial can be of the type ce_{ij}, and therefore the result will also be of this type. In the second case all degrees are even. Thus there are only cycles, and the result must be a diagonal matrix. □

As mentioned earlier, the following result follows easily from [Her], with another proof given in [BK], but a self-contained proof is included here for completeness.

Lemma 5. *If the image of p is not $\{0\}$ or the set of scalar matrices, then for any $i \neq j$ the matrix unit e_{ij} belongs to* $\mathrm{Im}\, p$. *The linear span of $L = \mathrm{Im}\, p$ must be either $\{0\}$, K, sl_n, or $M_n(K)$.*

Proof. Assume that the image is neither $\{0\}$ nor the set of scalar matrices. Then by Lemma 3 the image contains a non-diagonal matrix $p(x_1, \dots, x_m) = A$. Any x_i is a linear combination of matrix units. After opening brackets on the left-hand side we will have a linear combination of evaluations of p on matrix units, and on the right-hand side a non-diagonal matrix. From Lemma 4 it follows that any evaluation of p on matrix units is either diagonal or a matrix unit multiplied by some coefficient. Thus there is a matrix e_{ij} for $i \neq j$ in $\mathrm{Im}\, p$. Since any non-diagonal e_{kl} is conjugate to e_{ij}, all non-diagonal matrix units belong to the image. Thus all matrices with zeros on the diagonal belong to the linear span of the image. Taking matrices conjugate to these, we obtain $sl_n \subseteq L$. Thus L must be either sl_n or M_n. □

3.1. **The case $M_2(K)$.** Now we consider the case $n = 2$. We start by introducing the cones of main interest to us, drawing from Example 2.

Example 3.

(i) The set of non-zero nilpotent matrices constitutes an irreducible invariant cone, since these all have the same minimal and characteristic polynomial x^2.

(ii) The set of non-zero scalar matrices is an irreducible invariant cone.

(iii) Let $\tilde{K}$ denote the set of non-nilpotent, non-diagonalizable matrices in $M_2(K)$. Note that $A \in \tilde{K}$ precisely when A is non-scalar, but with equal non-zero eigenvalues, which is the case if and only if A is the sum of a non-zero scalar matrix with a non-zero nilpotent matrix. These are all conjugate when the scalar part is the identity, i.e., for matrices of the form

$$\begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix}, \qquad a \neq 0,$$

since these all have the same minimal and characteristic polynomials, namely $x^2 - 2x + 1$. It follows that $\tilde{K}$ is an irreducible invariant cone.

(iv) Let $\hat{K}$ denote the set of non-nilpotent matrices in $M_2(K)$ that have trace zero.

When Char $K \neq 2$, $\hat{K}$ is an irreducible invariant cone, since any such matrix has distinct eigenvalues and thus is conjugate to $\begin{pmatrix} \lambda & 0 \\ 0 & -\lambda \end{pmatrix}$.

When Char $K = 2$, $\hat{K}$ is an irreducible invariant cone, since any such matrix is conjugate to $\begin{pmatrix} \lambda & 1 \\ 0 & \lambda \end{pmatrix}$.

(v) $sl_2(K) \setminus \{0\}$ is the union of the two irreducible invariant cones of (i) and (iv). (The cases Char $K \neq 2$ and Char $K = 2$ are treated separately.)

(vi) Let C denote the set of non-zero matrices which are the sum of a scalar and a nilpotent matrix. Then C is the union of the following three irreducible invariant cones: The non-zero scalar matrices, the nilpotent matrices, and the non-zero scalar multiples of non-identity unipotent matrices. (All non-identity unipotent matrices are conjugate.)

From now on, we assume that K is a quadratically closed field. In particular, all of the eigenvalues of a matrix $A \in M_2(K)$ lie in K. One of our main ideas is to consider some invariant of the matrices in Im (p), and study the corresponding invariant cones. Here is the first such invariant that we consider.

Remark 3. Any non-nilpotent 2×2 matrix A over a quadratically closed field has two eigenvalues λ_1 and λ_2 such that at least one of them is non-zero. Therefore one can define the ratio of eigenvalues, which is well-defined up to taking reciprocals: $\frac{\lambda_1}{\lambda_2}$ and $\frac{\lambda_2}{\lambda_1}$. Thus, we will say that two non-nilpotent matrices have *different ratios* of eigenvalues if and only if their ratios of eigenvalues are not equal nor reciprocal.

We do have a well-defined mapping $\Pi : M_2(K) \to K$ given by $A \mapsto \frac{\lambda_1}{\lambda_2} + \frac{\lambda_2}{\lambda_1}$. This mapping is algebraic because

$$\frac{\lambda_1}{\lambda_2} + \frac{\lambda_2}{\lambda_1} = -2 + \frac{(\mathrm{tr} A)^2}{\det A}.$$

Remark 4. The set of non-scalar diagonalizable matrices with a fixed non-zero ratio r of eigenvalues (up to taking reciprocals) is an irreducible invariant cone. Indeed, this is true since any such diagonalizable matrix is conjugate to

$$\lambda \begin{pmatrix} 1 & 0 \\ 0 & r \end{pmatrix}.$$

3.2. **Images of semi-homogeneous polynomials.** We are ready to prove Theorem 1.

Lemma 6. *Suppose K is closed under d-roots, as well as being quadratically closed. If the image* Im p *of a semi-homogeneous polynomial p of weighted degree d contains an element of $\tilde{K}$, then* Im p *contains all of $\tilde{K}$.*

Proof. This is clear from Lemma 2(iii) together with Example 3, since $\tilde{K}$ is an irreducible invariant cone. ☐

Proof of Theorem 1. Assume that there are matrices $p(x_1, \dots, x_m)$ and $p(y_1, \dots, y_m)$ with different ratios of eigenvalues in the image of p. Consider the polynomial matrix $f(t) = p(tx_1 + (1-t)y_1, tx_2 + (1-t)y_2, \dots, tx_m + (1-t)y_m)$, and $\Pi \circ f$ where Π is defined in Remark 3. Write this non-constant rational function $\frac{\operatorname{tr}^2 f}{\det f}$ in lowest terms as $\frac{A(t)}{B(t)}$, where $A(t), B(t)$ are polynomials of degree $\leq 2 \deg p$ in the numerator and denominator.

An element $c \in K$ is in Im $(\Pi \circ f)$ iff there exists t such that $A - cB = 0$. (If for some t^*, $A(t^*) - cB(t^*) = 0$, then t^* would be a common root of A and B.) Let $d_c = \deg(A - cB)$. Then $d_c \leq \max(\deg A, \deg B) \leq 2 \deg p$, and $d_c = \max(\deg A, \deg B)$ for almost all c. Hence, the polynomial $A - cB$ is not constant and thus there is a root. Thus the image of $\frac{A(t)}{B(t)}$ is Zariski dense, implying that the image of $\frac{\operatorname{tr}^2 f}{\det f}$ is Zariski dense.

Hence, we may assume that Im p consists only of matrices having a fixed ratio r of eigenvalues. If $r \neq \pm 1$, the eigenvalues λ_1 and λ_2 are linear functions of $\operatorname{tr} p(x_1, \dots, x_m)$. Hence λ_1 and λ_2 are the elements of the algebra of generic matrices with traces, which is a domain by Proposition 1. But the two non-zero elements $p - \lambda_1 I$ and $p - \lambda_2 I$ have product zero, a contradiction.

We conclude that $r = \pm 1$. First assume $r = 1$. If Char $K \neq 2$, then p is a PI, by Lemma 1. If Char $K = 2$, then the image is either $sl_2(K)$ or $\hat{K}$, by Example 3(v).

Thus, we may assume $r = -1$ and Char $K \neq 2$. Hence, Im p consists only of matrices with $\lambda_1 = -\lambda_2$. By Lemma 1, there is a non-nilpotent matrix in the image of p. Hence, by Example 3(v), Im p is either $\hat{K}$ or strictly contains it and is all of $sl_2(K)$. □

We illuminate this result with some examples to show that certain cones may be excluded.

Example 4.

(i) The polynomial $g(x_1, x_2) = [x_1, x_2]^2$ has the property that $g(A, B) = 0$ whenever A is scalar, but g can take on a non-zero value whenever A is non-scalar. Thus, $g(x_1, x_2)x_1$ takes on all values except scalars. This polynomial is completely homogeneous, but not multilinear. (One can linearize in x_2 to make g linear in each variable except x_1, and the same idea can be applied to Formanek's construction [F1] of a central polynomial for any n.)

(ii) Let S be any finite subset of K. There exists a completely homogeneous polynomial p such that Im p is the set of all 2×2 matrices except the matrices with ratio of eigenvalues from S. The construction is as follows. Consider

$$f(x) = x \cdot \prod_{\delta \in S} (\lambda_1 - \lambda_2 \delta)(\lambda_2 - \lambda_1 \delta),$$

where $\lambda_{1,2}$ are eigenvalues of x. For each δ, $(\lambda_1 - \lambda_2 \delta)(\lambda_2 - \lambda_1 \delta)$ is a polynomial in $\operatorname{tr} x$ and $\operatorname{tr} x^2$. Thus $f(x)$ is a polynomial with traces, and, as noted above (by [Row, Theorem 1.4.12]), one can rewrite each trace in f as a fraction of multilinear central polynomials (see (3) in Proposition 1). After that we multiply the expression by the product of all the denominators, which we can take to have value 1. We obtain a completely homogeneous polynomial p for which the image is the cone under Im f and thus equals Im f. The image of p is the set of all non-nilpotent matrices with ratios of eigenvalues not belonging to S.

(iii) The image of a completely homogeneous polynomial evaluated on 2×2 matrices can also be $\hat{K}$. Take $f(x,y) = [x,y]^3$. This is the product of $[x,y]^2$ and $[x,y]$. $[x,y]^2$ is a central polynomial, and therefore tr $f = 0$. However, there are no nilpotent matrices in Im p because if $[A,B]^3$ is nilpotent, then $[A,B]$ (which is a scalar multiple of $[A,B]^3$) is nilpotent and therefore $[A,B]^2 = 0$ and $[A,B]^3 = 0$.

(iv) Consider the polynomial

$$p(x_1,x_2,y_1,y_2) = [(x_1x_2)^2,(y_1y_2)^2]^2 + [(x_1x_2)^2,(y_1y_2)^2][x_1y_1,x_2y_2]^2.$$

Then p takes on all scalar values (since it becomes central by specializing $x_1 \mapsto x_2$ and $y_1 \mapsto y_2$), but also takes on all nilpotent values, since specializing $x_1 \mapsto I + e_{12}$, $x_2 \mapsto e_{22}$, and $y_1 \mapsto e_{12}$, and $y_2 \mapsto e_{21}$ sends p to

$$[(e_{12}+e_{22})^2, e_{11}^2]^2 + [(e_{12}+e_{22})^2, e_{11}^2][e_{12},e_{21}] = 0 - e_{12}(e_{11}-e_{22}) = e_{12}.$$

We claim that Im p does not contain any matrix $a = p(\bar{x}_1,\bar{x}_2,\bar{y}_1,\bar{y}_2)$ in $\tilde{K}$. Otherwise, the matrix $[(\bar{x}_1\bar{x}_2)^2,(\bar{y}_1\bar{y}_2)^2][\bar{x}_1\bar{y}_1,\bar{x}_2\bar{y}_2]^2$ would be the difference of a matrix having equal eigenvalues and a scalar matrix, but of trace 0, and so would have both eigenvalues 0 and thus be nilpotent. Thus $[(\bar{x}_1\bar{x}_2)^2,(\bar{y}_1\bar{y}_2)^2]$ would also be nilpotent, implying that the scalar term $[(\bar{x}_1\bar{x}_2)^2,(\bar{y}_1\bar{y}_2)^2]^2$ equals zero, implying that a is nilpotent, a contradiction.

Im p also contains all matrices having two distinct eigenvalues. We conclude that Im $p = M_2(K) \setminus \tilde{K}$.

Remark 5. In Example 4(iv), the intersection S of Im p with the discriminant surface is defined by the polynomial $\mathrm{tr}(p(x_1,\dots,x_m))^2 - 4\det(p(x_1,\dots,x_m)) = (\lambda_1-\lambda_2)^2$. S is the union of two irreducible varieties (its scalar matrices and the non-zero nilpotent matrices), and thus S is a reducible variety. Thus, we see that the discriminant surface of a polynomial p of the algebra of generic matrices can be reducible, even if it is not divisible by any trace polynomial. Such an example could not exist for p multilinear, since then, by the same sort of argument as given in the proof of Theorem 1, the discriminant surface would give a generic zero divisor in Amitsur's universal division algebra UD of Proposition 1, a contradiction. In fact, we will also see that the image of a multilinear polynomial cannot be as in Example 4(iv).

3.3. **Images of non-homogeneous polynomials.** Now we consider briefly the general case. One can write any polynomial $p(x_1,\dots,x_m)$ as $p = h_k + \cdots + h_n$, where the h_i are semi-homogeneous polynomials of weighted degree i.

Proposition 2. *With the notation as above, assume there are weights $(w_1,\dots,w_m)$ such that the polynomial h_n has image dense in $M_2(K)$. Then* Im p *is dense in* $M_2(K)$.

Proof. Consider

$$p(\lambda_1^w x_1,\dots,\lambda_m^w x_m) = \sum_{i=k}^{n} h_i\lambda^i.$$

One can write $\tilde{P} = \lambda^{-n}p(\lambda_1^w x_1,\dots,\lambda_m^w x_m)$ as a polynomial in $x_1,\dots,x_m$ and $\varepsilon = \frac{1}{\lambda}$. The matrix polynomial is the set of four polynomials $p_{1,1},p_{1,2},p_{2,1},p_{2,2}$, which we claim are independent. If there is some polynomial h in four variables such that $h(p_{1,1},p_{1,2},p_{2,1},p_{2,2}) = 0$, then h should vanish on four polynomials of $\tilde{P}$ for each ε, in particular for $\varepsilon = 0$, a contradiction. $\square$

Remark 6. The case remains open when $p(x_1, \dots, x_m)$ is a polynomial for which there are no weights $(w_1, \dots, w_m)$ such that one can write $p = h_k + \dots + h_n$, where h_i is semi-homogeneous of weighted degree i and h_n has image dense in M_2.

Example 5. For Char $K \neq 2$ we give an example of such a polynomial whose middle term has image dense in $M_2(K)$. Take the polynomial $f(x,y) = [x,y] + [x,y]^2$. It is not hard to check that Im f is the set of all matrices with eigenvalues c^2+c and c^2-c. Consider $p(\alpha_1, \alpha_2, \beta_1, \beta_2) = f(\alpha_1 + \beta_1^2, \alpha_2 + \beta_2^2)$. The polynomials f and p have the same images. Now let us open the brackets. The term of degree 4 is $h_4 = [\alpha_1, \alpha_2]^2 + [\beta_1^2, \beta_2^2]$. The image of h_4 is all of $M_2(K)$, because $[\alpha_1, \alpha_2]^2$ can be any scalar matrix and $[\beta_1^2, \beta_2^2]$ can be any trace zero matrix. However the image of p is the set of all matrices with eigenvalues c^2+c and c^2-c.

3.4. **Images of multilinear polynomials.**

Lemma 7. *If $A, B \in$ Im p have different ratios of eigenvalues, then* Im p *contains matrices having arbitrary ratios of eigenvalues $\frac{\lambda_1}{\lambda_2} \in K$.*

Proof. Assume that $p(x_1, \dots, x_m) = A$ and $p(y_1, \dots, y_m) = B$. We may lift the x_i and y_i to generic matrices. Then take

$$f(T_1, T_2, \dots, T_m) = p(\tau_1 x_1 + t_1 y_1, \dots, \tau_m x_m + t_m y_m),$$

where $T_i = (t_i, \tau_i) \in K^2$. The polynomial f is linear with respect to all T_i.

In view of Remark 3, it is enough to show that the ratio $\frac{(\mathrm{tr} f)^2}{\det f}$ takes on all values. Fix $T_1, \dots, T_{i-1}, T_{i+1}, \dots, T_m$ to be generic pairs.

Since $\frac{(\mathrm{tr} A)^2}{\det A} \neq \frac{(\mathrm{tr} B)^2}{\det B}$, $\frac{(\mathrm{tr} f)^2}{\det f}$ is not constant. But $\frac{(\mathrm{tr} f)^2}{\det f}$ is the ratio of nonzero quadratic polynomials, and K is quadratically closed, so we can solve $\frac{(\mathrm{tr} f)^2}{\det f} = c$ for any $c \in K$, yielding the assertion. $\square$

Lemma 8. *If there exist $\lambda_1 \neq \pm\lambda_2$ with a collection of matrices $(E_1, E_2, \dots, E_m)$ such that $p(E_1, E_2, \dots, E_m)$ has eigenvalues λ_1 and λ_2, then all diagonalizable matrices lie in* Im p.

Proof. Applying Lemma 4 to the hypothesis, we obtain a matrix

$$\begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \in \mathrm{Im}\, p,\ \ \lambda_1 \neq \pm\lambda_2$$

which is an evaluation of p on matrix units e_{ij}. Consider the following mapping χ acting on the indices of the matrix units: $\chi(e_{ij}) = e_{3-i,3-j}$. Now take the polynomial

$$f(T_1, T_2, \dots, T_m) = p(\tau_1 x_1 + t_1 \chi(x_1), \dots, \tau_m x_m + t_m \chi(x_m)),$$

where $T_i = (t_i, \tau_i) \in K^2$, which is linear with respect to each T_i. Let us open the brackets. We obtain 2^m terms and for each of them the degrees of all vertices stay even. (The edge 12 becomes 21, which does not change degrees, and the edge 11 becomes 22, which decreases the degree of the vertex 1 by two and increases the degree of the vertex 2 by two.) Thus all terms remain diagonal. Consider generic pairs $T_1, \dots, T_m \in K^2$. For each i consider the polynomial $\tilde{f}_i(T_i^*) = f(T_1, \dots, T_{i-1}, T_i + T_i^*, T_{i+1}, \dots, T_m)$. For at least one i the ratio of eigenvalues of $\tilde{f}_i$ must be different from ± 1. (Otherwise the ratio of the eigenvalues of $\tilde{f}_i$ equals ± 1 for all i, implying $\lambda_1 = \pm\lambda_2$, a contradiction.)

Fix i such that the ratio of the eigenvalues of $\tilde{f}_i$ is not ± 1. By linearity, Im $(\tilde{f}_i)$ takes on values with all possible ratios of eigenvalues; hence, the cone under Im $(\tilde{f}_i)$ is the set of all diagonal matrices. Therefore by Lemma 2 all diagonalizable matrices lie in the image of p. □

Lemma 9. *If p is a multilinear polynomial evaluated on the matrix ring $M_2(K)$, then* Im p *is either* $\{0\}$*,* K*,* sl_2*,* $M_2(K)$*, or* $M_2(K) \setminus \tilde{K}$*.*

Proof. In view of Lemma 2, we are done unless Im p contains a non-scalar matrix. By Lemma 5, the linear span of Im p is sl_2 or $M_2(K)$. We treat the characteristic 2 and characteristic $\neq 2$ cases separately.

CASE I. Char $K = 2$. Consider the set

$$\Theta = \{p(E_1, \dots, E_m), \quad \text{where the } E_j \text{ are matrix units}\}.$$

If the linear span of the image is not sl_2, then Θ contains at least one non-scalar diagonal matrix Diag$\{\lambda_1, \lambda_2\}$, so $\lambda_1 \neq -\lambda_2$ (since $+1 = -1$). Hence by Lemma 8, all diagonalizable matrices belong to Im p. Thus, Im p contains $M_2(K) \setminus \tilde{K}$.

If the linear span of the image of p is sl_2, then by Lemma 4 the identity matrix (and thus all scalar matrices) and e_{12} (and thus all nilpotent matrices) belong to the image. On the other hand, in characteristic 2, any matrix sl_2 is conjugate to a matrix of the form $\lambda_1 I + \lambda_2 e_{1,2}$, and we consider the invariant $\frac{\lambda_2}{\lambda_1}$. Take $x_1, \dots, x_m$ to be generic matrices. If $p(x_1, \dots, x_m)$ were nilpotent, then Im p would consist only of nilpotent matrices, which is impossible. By Example 3(v), $p(x_1, \dots, x_m)$ is not scalar and not nilpotent, and thus is a matrix from $\tilde{K}$. Hence, $\tilde{K} \subset$ Im p, by Lemma 6. Thus, all trace zero matrices belong to Im p.

CASE II. Char $K \neq 2$. Again assume that the image is not $\{0\}$ or the set of scalar matrices. Then by Lemma 5 we obtain that $e_{12} \in$ Im p. Thus all nilpotent matrices lie in Im p. If the image consists only of matrices of trace zero, then by Lemma 5 there is at least one matrix in the image with a non-zero diagonal entry. By Lemma 4 there is a set of matrix units that maps to a non-zero diagonal matrix which, by assumption, is of trace zero and thus is $\begin{pmatrix} c & 0 \\ 0 & -c \end{pmatrix}$. By Lemma 2 and Example 3, Im p contains all trace zero 2×2 matrices.

Assume that the image contains a matrix with non-zero trace. Then by Lemma 5 the linear span of the image is $M_2(K)$, and together with Lemma 4 we have at least two diagonal linearly independent matrices in the image. Either these matrices have ratios of eigenvalues $(\lambda_1 : \lambda_2)$ and $(\lambda_2 : \lambda_1)$ for $\lambda_1 \neq \pm\lambda_2$ or these matrices have non-equivalent ratios. In the first case we can use Lemma 8, which says that all diagonalizable matrices lie in the image. If at least one of these matrices has ratio not equal to ± 1, then in the second case we also use Lemma 8 and obtain that all diagonalizable matrices lie in the image. If these matrices are such that the ratios of their eigenvalues are respectively 1 and -1, then we use Lemma 7 and obtain that all diagonalizable matrices with distinct eigenvalues lie in the image. By assumption, in this case, scalar matrices also belong to the image. Therefore we obtain that for any ratio $(\lambda_1 : \lambda_2)$ there is a matrix $A \in$ Im p having such a ratio of eigenvalues. Using Lemmas 2 and 6, we obtain that the image of p can be either $\{0\}$, K, sl_2, $M_2(K)$, or $M_2(K) \setminus \tilde{K}$. □

Lemma 10. *If p is a multilinear polynomial evaluated on the matrix ring $M_2(K)$, where K is a quadratically closed field of characteristic 2, then* Im p *is either $\{0\}$, K, sl_2, or $M_2(K)$.*

Proof. In view of Lemma 9, it suffices to assume that the image of p is $M_2(K) \setminus \tilde{K}$. Let $x_1, \dots, x_m, y_1, \dots, y_m$ be generic matrices. Consider the polynomials

$$b_i = p(x_1, \dots, x_{i-1}, y_i, x_{i+1}, \dots, x_m).$$

Let $p_i(x_1, \dots, x_m, y_i) = p\mathrm{tr}(b_i) + \mathrm{tr}(p)b_i$. Hence p_i can be written as

$$p_i = p(x_1, \dots, x_{i-1}, x_i\mathrm{tr}(b_i) + y_i\mathrm{tr}(p), x_{i+1}, \dots, x_m).$$

Therefore Im $p_i \subseteq$ Im p. Also if $a \in$ Im p_i, then

$$\mathrm{tr}(a) = \mathrm{tr}(p\,\mathrm{tr}(b_i) + \mathrm{tr}(p)\,b_i) = 2\,\mathrm{tr}(p)\,\mathrm{tr}(b_i) = 0.$$

Thus, Im p_i consists only of trace-zero matrices that belong to the image of p. Excluding $\tilde{K}$, the only trace-zero matrices are nilpotent or scalar. Thus, for each i, $p_i(x_1, \dots, x_m, y_i)$ is either scalar or nilpotent. However, the p_i are the elements of the algebra of free matrices with traces, which is a domain. Thus, $p_i(x_1, \dots, x_m, y_i)$ cannot be nilpotent. Hence for all $i = 1, \dots, m$, $p_i(x_1, \dots, x_m, y_i)$ is scalar. In this case, changing variables leaves the plane $\langle p, I \rangle$ invariant. Therefore, $\dim(\mathrm{Im}\ p) = 2$, a contradiction. □

Lemma 11. *If p is a multilinear polynomial evaluated on the matrix ring $M_2(K)$ (where K is a quadratically closed field of characteristic not 2), then* Im p *is either $\{0\}$, K, sl_2, or $M_2(K)$.*

Proof. We assume that Im $p = M_2(K) \setminus \tilde{K}$. A linear change of the variable in position i gives us the line $A + tB$ in the image, where $A = p(x_1, \dots, x_m)$ and $B = p(x_1, \dots, x_{i-1}, y_i, x_{i+1}, \dots, x_m)$. Take the function that maps t to $f(t) = (\lambda_1 - \lambda_2)^2$, where λ_i are the eigenvalues of $A + tB$. Evidently

$$f(t) = (\lambda_1 - \lambda_2)^2 = (\lambda_1 + \lambda_2)^2 - 4\lambda_1\lambda_2 = (\mathrm{tr}(A + tB))^2 - 4\det(A + tB),$$

so our function f is a polynomial of deg ≤ 2 evaluated on the entries of $A + tB$, and thus is a polynomial in t.

There are three possibilities: Either $\deg_t f \leq 1$, or f is the square of another polynomial, or f vanishes at two different values of t (say, t_1 and t_2). (Note that here we use that the field is quadratically closed.) This polynomial f vanishes if and only if the two eigenvalues of $A + tB$ are equal, and this happens in two cases (according to Lemma 9): $A + tB$ is scalar or $A + tB$ is nilpotent. Thus either both $A + t_iB$ are scalar or $A + t_1B$ is scalar and $A + t_2B$ is nilpotent or both $A + t_iB$ are nilpotent. The first case implies that A and B are scalars, which is impossible. The second case implies that the matrix $A + \frac{t_1+t_2}{2}B \in \tilde{K}$, which is also impossible.

We are left with the third case, which implies that $\mathrm{tr}A = \mathrm{tr}B = 0$, and we claim that this is also impossible. If $\deg_t f \leq 1$, then for large t, the difference $\lambda_1 - \lambda_2$ of the eigenvalues of $A + tB$ is much less than t, so the difference between eigenvalues of B must be 0, a contradiction.

It follows that $f(t) = (\lambda_1 - \lambda_2)^2$ must be the square of a polynomial (with respect to t). Thus $\lambda_1 - \lambda_2 = a + tb$, where a and b are functions on the entries of the matrices $x_1, \dots, x_m, y_i$. Note that a is the difference of eigenvalues of A, and b is the difference of eigenvalues of B. Thus

$$a(x_1, \dots, x_m, y_i) = b(x_1, \dots, x_{i-1}, y_i, x_{i+1}, \dots, x_m, x_i). \tag{4}$$

Note that $(\lambda_1 - \lambda_2)^2 = a^2 + 2abt + b^2t^2$, which means that a^2, b^2 and ab are polynomials. (Here we use Char $K \neq 2$.) Thus, $\frac{a}{b} = \frac{a^2}{ab}$ is a rational function. Therefore there are polynomials p_1, p_2 and q such that $a = p_1\sqrt{q}$ and $b = p_2\sqrt{q}$. Without loss of generality, q does not have square divisors. By (4) we have that q does not depend on x_i and y_i. Now consider any change of other variables. The function a is the difference of eigenvalues of $A = p(x_1, \dots, x_m)$, so it remains unchanged. Thus q also does not depend on the other variables. Recalling that λ_1 and λ_2 are the eigenvalues of $p(x_1, \dots, x_m)$ we conclude that $\lambda_1 - \lambda_2$ is a polynomial. $\lambda_1 + \lambda_2 = \mathrm{tr}(p)$ is also a polynomial and hence the λ_i are polynomials, which obviously are invariant under conjugation since any conjugate is the square of some other conjugate. Hence, the λ_i are polynomials of traces, by Donkin's Theorem quoted above. Now consider the polynomials $(p - \lambda_1 I)$ and $(p - \lambda_2 I)$, which are elements of the algebra of free matrices with traces, which we noted above is a domain. Both are not zero, but their product is zero, a contradiction. $\square$

Remark. A proof of this lemma with more detailed calculations is given in the arXiv (http://arxiv.org/abs/1005.0191).

Finally, Theorem 2 follows from Lemmas 10 and 11.

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