NEW LOWER BOUNDS FOR THE BORDER RANK OF MATRIX MULTIPLICATION

J.M. LANDSBERG AND GIORGIO OTTAVIANI

Abstract. The border rank of the matrix multiplication operator for $\mathbf{n}\times\mathbf{n}$ matrices is a standard measure of its complexity. Using techniques from algebraic geometry and representation theory, we show the border rank is at least $2\mathbf{n}^2-\mathbf{n}$. Our bounds are better than the previous lower bound (due to Lickteig in 1985) of $\frac{3}{2}\mathbf{n}^2+\frac{\mathbf{n}}{2}-1$ for all $\mathbf{n}\geq 3$. The bounds are obtained by finding new equations that bilinear maps of small border rank must satisfy, i.e., new equations for secant varieties of triple Segre products, that matrix multiplication fails to satisfy.

1. Introduction and statement of results

Finding lower bounds in complexity theory is considered difficult. For example, chapter 14 of [1] is "Circuit lower bounds: Complexity theory's Waterloo". The complexity of matrix multiplication is roughly equivalent to the complexity of many standard operations in linear algebra, such as taking the determinant or inverse of a matrix. A standard measure of the complexity of an operation is the minimal size of an arithmetic circuit needed to perform it. The exponent of matrix multiplication ω is defined to be $\underline{\lim}_{\mathbf{n}}\log_{\mathbf{n}}$ of the arithmetic cost to multiply $\mathbf{n}\times\mathbf{n}$ matrices, or equivalently, $\underline{\lim}_{\mathbf{n}}\log_{\mathbf{n}}$ of the minimal number of multiplications needed [3, Props. 15.1, 15.10]. Determining the complexity of matrix multiplication is a central question of practical importance. We give new lower bounds for its complexity in terms of border rank. These lower bounds are used to prove further lower bounds for tensor rank in [8, 12].

Let A,B,C be vector spaces, with dual spaces A^*,B^*,C^*, and let $T:A^*\times B^*\to C$ be a bilinear map. The *rank* of T is the smallest r such that there exist $a_1,\dots,a_r\in A$, $b_1,\dots,b_r\in B$, $c_1,\dots,c_r\in C$ such that $T(\alpha,\beta)=\sum_{i=1}^r a_i(\alpha)b_i(\beta)c_i$. The *border rank* of T is the smallest r such that T can be written as a limit of a sequence of bilinear maps of rank r. Let $\underline{\mathbf{R}}(T)$ denote the border rank of T. See [9] or [3] for more on the rank and border rank of tensors, especially the latter for their relation to other measures of complexity.

Let $M_{\langle\mathbf{m},\mathbf{n},\mathbf{l}\rangle}:Mat_{\mathbf{m}\times\mathbf{n}}\times Mat_{\mathbf{n}\times\mathbf{l}}\to Mat_{\mathbf{m}\times\mathbf{l}}$ denote the matrix multiplication operator. One has (see, e.g., [3, Props. 15.1, 15.10]) that $\omega=\underline{\lim}_{\mathbf{n}}(\log_{\mathbf{n}}\underline{\mathbf{R}}(M_{\langle\mathbf{n},\mathbf{n},\mathbf{n}\rangle}))$. Naïvely $\underline{\mathbf{R}}(M_{\langle\mathbf{m},\mathbf{n},\mathbf{l}\rangle})\leq\mathbf{mnl}$ via the standard algorithm. In 1969, V. Strassen [18] showed that $\mathbf{R}(M_{\langle 2,2,2\rangle})\leq 7$ and, as a consequence, $\mathbf{R}(M_{\langle\mathbf{n},\mathbf{n},\mathbf{n}\rangle})\leq\mathcal{O}(\mathbf{n}^{2.81})$. Further upper bounds have been derived since then by numerous authors, with the current record $\mathbf{R}(M_{\langle\mathbf{n},\mathbf{n},\mathbf{n}\rangle})\leq\mathcal{O}(\mathbf{n}^{2.3727})$ [20]. In 1983 Strassen showed [17] that $\underline{\mathbf{R}}(M_{\langle\mathbf{n},\mathbf{n},\mathbf{n}\rangle})\geq\frac{3}{2}\mathbf{n}^2$, and shortly thereafter T. Lickteig [11] showed $\underline{\mathbf{R}}(M_{\langle\mathbf{n},\mathbf{n},\mathbf{n}\rangle})\geq\frac{3}{2}\mathbf{n}^2+\frac{\mathbf{n}}{2}-1$. Since then no further general lower bound had been found (although it is now known that $\underline{\mathbf{R}}(M_{\langle 2,2,2\rangle})=7$, see [7, 5]), and a completely different proof (using methods proposed by Mulmuley and Sohoni for Geometric complexity theory) that $\underline{\mathbf{R}}(M_{\langle\mathbf{n},\mathbf{n},\mathbf{n}\rangle}))\geq\frac{3}{2}\mathbf{n}^2-2$ was given in [**?**].

Our results are as follows:

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Theorem 1.1. *Let* $\mathbf{n} \leq \mathbf{m}$. *For all* $\mathbf{l} \geq 1$

$$\underline{\mathbf{R}}(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle}) \geq \frac{\mathbf{nl}\,(\mathbf{n}+\mathbf{m}-1)}{\mathbf{m}}. \tag{1}$$

Corollary 1.2.

$$\underline{\mathbf{R}}(M_{\langle \mathbf{n},\mathbf{n},\mathbf{l}\rangle}) \geq 2\mathbf{nl} - \mathbf{l} \tag{2}$$

$$\underline{\mathbf{R}}(M_{\langle \mathbf{n},\mathbf{n},\mathbf{n}\rangle}) \geq 2\mathbf{n}^2 - \mathbf{n}. \tag{3}$$

For 3×3 matrices, the state of the art is now $15 \leq \underline{\mathbf{R}}(M_{\langle 3,3,3\rangle}) \leq 21$, the upper bound is due to Schönhage [16].

Remark 1.3. The best lower bound for the *rank* of matrix multiplication, was, until recently, $\mathbf{R}(M_{\langle \mathbf{n},\mathbf{n},\mathbf{n}\rangle}) \geq \frac{5}{2}\mathbf{n}^2 - 3\mathbf{n}$, due to to Bläser, [2]. After this paper was posted on arXiv, and using Theorem 1.2, it was shown that $\mathbf{R}(M_{\langle \mathbf{n},\mathbf{n},\mathbf{n}\rangle}) \geq 3\mathbf{n}^2 - 4\mathbf{n}^{2/3} - \mathbf{n}$ by Landsberg in [8] and then, pushing the same methods further, A. Massarenti and E. Raviolo showed $\mathbf{R}(M_{\langle \mathbf{n},\mathbf{n},\mathbf{n}\rangle}) \geq 3\mathbf{n}^2 - 2\sqrt{2}\mathbf{n}^{3/2} - 3\mathbf{n}$ in [12].

Our bounds come from explicit equations that bilinear maps of low border rank must satisfy. These equations are best expressed in the language of tensors. Our method is similar in nature to the method used by Strassen to get his lower bounds - we find explicit polynomials that tensors of low border rank must satisfy, and show that matrix multiplication fails to satisfy them. Strassen found his equations via linear algebra - taking the commutator of certain matrices. We found ours using representation theory and algebraic geometry. (Algebraic geometry is not needed for presenting the results. For its role in our method see [10].) More precisely, in §2 we define, for every p, a linear map

$$(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle})_A^{\wedge p} \colon \mathbb{C}^{\mathbf{nl}\binom{\mathbf{mn}}{p}} \to \mathbb{C}^{\mathbf{ml}\binom{\mathbf{mn}}{p+1}} \tag{4}$$

and we prove that $\underline{\mathbf{R}}(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle}) \geq \binom{\mathbf{mn}-1}{p}^{-1} \operatorname{rank}\left[(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle})_A^{\wedge p}\right]$. In order to prove Theorem 1.1, we specialize this map for a judiciously chosen p to a subspace where it becomes injective. The above-mentioned equations are the minors of the linear map $(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle})_A^{\wedge p}$.

The map (4) is of interest in its own right, we discuss it in detail in §4. This is done with the help of representation theory - we explicitly describe the kernel as a sum of irreducible representations labeled by Young diagrams.

Remark 1.4. It is conjectured in the computer science community that $\underline{\mathbf{R}}(M_{\langle \mathbf{n},\mathbf{n},\mathbf{n}\rangle})$ grows like $\mathcal{O}(\mathbf{n}^{2+\epsilon})$ for any $\epsilon > 0$. A truly significant lower bound would be a function that grew like $\mathbf{n}^2 h(\mathbf{n})$ where h is an increasing function. No super-linear lower bound on the complexity of any explicit tensor (or any computational problem) is known, see [1, 19].

From a mathematician's perspective, all known equations for secant varieties of Segre varieties that have a geometric model arise by translating multi-linear algebra to linear algebra, and it appears that the limit of this technique is roughly the "input size" $3n^2$.

Remark 1.5. The methods used here should be applicable to lower bound problems coming from the *Geometric Complexity Theory* (GCT) introduced by Mulmuley and Sohoni [13], in particular to separate the determinant (small weakly skew circuits) from polynomials with small formulas (small tree circuits).

Overview. In §2 we describe the new equations to test for border rank in the language of tensors. Theorem 1.1 is proved in §3. We give a detailled analysis of the kernel of the map (4) in sections §4 and §4.2. This analysis should be very useful for future work. We conclude in §5 with a review of Lickteig's method for purposes of comparison. An appendix §6 with basic facts from representation theory that we use is included for readers not familiar with the subject.

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2. The new equations

Let A, B, C be complex vector spaces of dimensions $\mathbf{a}, \mathbf{b}, \mathbf{c}$, with $\mathbf{b} \leq \mathbf{c}$, and with dual vector spaces A^*, B^*, C^*. Then $A \otimes B \otimes C$ may be thought of as the space of bilinear maps $A^* \times B^* \to C$.

The most naïve equations for border rank are the so-called *flattenings*. Given $T \in A \otimes B \otimes C$, consider T as a linear map $B^* \to A \otimes C$ and write T_B for this map. Then $\underline{\mathbf{R}}(T) \geq \mathrm{rank}(T_B)$ and similarly for the analogous T_A, T_C. The rank of a linear map is determined by taking minors.

2.1. **Strassen's equations.** Strassen's equations [17] may be understood as follows (see §2.2 for the geometric origin of this perspective). As described in [14], tensor T_B with Id_A to obtain a linear map $B^* \otimes A \to A \otimes A \otimes C$ and skew-symmetrize the $A \otimes A$ factor to obtain a map

$$T_A^{\wedge 1} : B^* \otimes A \to \Lambda^2 A \otimes C.$$

If T is generic, then one can show that $T_A^{\wedge 1}$ will have maximal rank, and if $T = a \otimes b \otimes c$ is of rank one, $\mathrm{rank}((a \otimes b \otimes c)_A^{\wedge 1}) = \mathbf{a} - 1$. To see this, expand $a = a_1$ to a basis $a_1, \ldots, a_{\mathbf{a}}$ of A with dual basis $\alpha^1, \ldots, \alpha^{\mathbf{a}}$ of A^*. Then $T_A^{\wedge 1} = \sum_i [\alpha^i \otimes b] \otimes [a_1 \wedge a_i \otimes c]$, so the image is isomorphic to $(A/a_1) \otimes c$.

It follows that $\underline{\mathbf{R}}(T) \geq \frac{\mathrm{rank}(T_A^{\wedge 1})}{\mathbf{a}-1}$. Thus the best bound one could hope for with this technique is up to $r = \frac{\mathbf{ba}}{\mathbf{a}-1}$. The minors of size $r(\mathbf{a}-1)+1$ of $T_A^{\wedge 1}$ give equations for the tensors of border rank at most r in $A \otimes B \otimes C$. This is most effective when $\mathbf{a} = 3$.

When $\mathbf{a} > 3$, for each 3-plane $A' \subset A$, consider the restriction $T|_{A' \otimes B \otimes C}$ and the corresponding equations, to obtain equations for the tensors of border rank at most r in $A \otimes B \otimes C$ as long as $r \leq \frac{3\mathbf{b}}{2}$. This procedure is called *inheritance* (see [9, §7.4.2]).

We consider the following generalizations: tensor T_B with $Id_{\Lambda^p A}$ to obtain a linear map $B^* \otimes \Lambda^p A \to \Lambda^p A \otimes A \otimes C$ and skew-symmetrize the $\Lambda^p A \otimes A$ factor to obtain a map

$$T_A^{\wedge p} : B^* \otimes \Lambda^p A \to \Lambda^{p+1} A \otimes C. \tag{5}$$

To avoid redundancies, assume $\mathbf{b} \leq \mathbf{c}$ and $p \leq \lceil \frac{\mathbf{a}}{2} \rceil - 1$. Then, if $T = a \otimes b \otimes c$ is of rank one,

$$\mathrm{rank}((a \otimes b \otimes c)_A^{\wedge p}) = \binom{\mathbf{a}-1}{p}.$$

To see this, compute $T_A^{\wedge p} = \sum [\alpha^{i_1} \wedge \cdots \wedge \alpha^{i_p} \otimes b] \otimes [a_1 \wedge a_{i_1} \wedge \cdots \wedge a_{i_p} \otimes c]$, to conclude the image is isomorphic to $\Lambda^p (A/a_1) \otimes c$.

In summary:

Theorem 2.1. *Interpret $T \in A \otimes B \otimes C$ as a linear map $B^* \to A \otimes C$ and let $T_A^{\wedge p} : B^* \otimes \Lambda^p A \to \Lambda^{p+1} A \otimes C$ be the map obtained by skew-symmetrizing $T \otimes Id_{\Lambda^p A}$ in the $A \otimes \Lambda^p A$ factor. Then*

$$\underline{\mathbf{R}}(T) \geq \frac{\mathrm{rank} T_A^{\wedge p}}{\binom{\mathbf{a}-1}{p}}.$$

Proof. Let $r=\underline{\mathbf{R}}(T)$ and let $T_\epsilon=\sum_{i=1}^r T_{\epsilon,i}$ be such that $\mathbf{R}(T_{\epsilon,i})=1$ and $\lim_{\epsilon\to 0}T_\epsilon=T$. Then

$$\mathrm{rank} T_A^{\wedge p}\le \mathrm{rank}(T_\epsilon)_A^{\wedge p}\le \sum_{i=1}^r \mathrm{rank}(T_{\epsilon,i})_A^{\wedge p}=r\binom{\mathbf{a}-1}{p}$$

□

Remark 2.2. Alternatively, one can compute the rank using the vector bundle techniques of [10].

When this article was posted on arXiv, we only knew that the minors of size $r\binom{\mathbf{a}-1}{p}+1$ of the maps $T_A^{\wedge p}$ gave nontrivial equations for tensors of border rank at most r in $A{\otimes}B{\otimes}C$ for $r\le 2\mathbf{a}-\sqrt{\mathbf{a}}$. Then, in [6], it was shown they actually give nontrivial equations up to the maximum $2\mathbf{b}-1$.

We record the following proposition which follows from Stirling's formula and the discussion above.

Proposition 2.3. *The equations for the variety of tensors of border rank at most r in $A{\otimes}B{\otimes}C$ obtained by taking minors of $T_A^{\wedge p}$ are of degree $r\binom{\mathbf{a}-1}{p}+1$. In particular, when r approaches the upper bound $2\mathbf{b}$ and $p=\lceil\frac{\mathbf{a}}{2}\rceil-1$, the equations are asymptotically of degree $\sqrt{\frac{2}{\pi}}\,\frac{2^{\mathbf{a}}\mathbf{b}}{\sqrt{\mathbf{a}-1}}$.*

Theorem 1.1 is obtained by applying the inheritance principle to the case of an $(\mathbf{n}+\mathbf{m}-1)$-plane $A'\subset A=\mathbb{C}^{\mathbf{nm}}$.

2.2. **Origin of the equations corresponding to minors of** (5)**.** This subsection is not used in the proof of the main theorem. We work in projective space as the objects we are interested in are invariant under rescaling.

Let $Seg(\mathbb{P}A\times\mathbb{P}B\times\mathbb{P}C)\subset\mathbb{P}(A{\otimes}B{\otimes}C)$ denote the Segre variety of rank one tensors and let $\sigma_r(Seg(\mathbb{P}A\times\mathbb{P}B\times\mathbb{P}C))$ denote its r-th secant variety, the variety of tensors of border rank at most r.

In [10] we introduced a generalization of flattenings, called *Young flattenings*, which in the present context is as follows: Irreducible polynomial representations of the general linear group $GL(A)$ correspond to partitions $\pi=(\pi_1,\dots,\pi_{\mathbf{a}})$, see §6.1. Let $S_\pi A$ denote the corresponding $GL(A)$-module. Consider representations $S_\pi A, S_\mu B, S_\nu C$, and the identity maps $Id_{S_\pi A}\in S_\pi A{\otimes}S_\pi A^*$ etc... Then we may consider

$$T{\otimes}Id_{S_\pi A}{\otimes}Id_{S_\mu A}{\otimes}Id_{S_\nu A}\in A{\otimes}B{\otimes}C{\otimes}S_\pi A{\otimes}S_\pi A^*{\otimes}S_\mu B{\otimes}S_\mu B^*{\otimes}S_\nu C{\otimes}S_\nu C^*$$

We may decompose $S_\pi A{\otimes}A$ according to the Pieri rule (see §6.3) and project to one irreducible component, say $S_{\tilde\pi}A$, where $\tilde\pi$ is obtained by adding a box to π, and similarly for C, while for B we may decompose $S_\mu B^*{\otimes}B$ and project to one irreducible component, say $S_{\hat\mu}B^*$, where $\hat\mu$ is obtained by deleting a box from μ. The upshot is a tensor

$$T'\in S_{\tilde\pi}A{\otimes}S_\mu B{\otimes}S_{\tilde\nu}C{\otimes}S_\pi A^*{\otimes}S_{\hat\mu}B^*{\otimes}S_\nu C^*$$

which we may then consider as a linear map, e.g.,

$$T':S_\pi A{\otimes}S_\mu B^*{\otimes}S_\nu C\to S_{\tilde\pi}A{\otimes}S_{\hat\mu}B^*{\otimes}S_{\tilde\nu}C$$

and rank conditions on T' may give border rank conditions on T.

Returning to the minors of (5), the minors of size $t+1$ of $T_A^{\wedge p}$ give modules of equations which are contained in

(6)
$$\Lambda^{t+1}(\Lambda^pA{\otimes}B^*){\otimes}\Lambda^{t+1}(\Lambda^{p+1}A^*{\otimes}C^*)=\bigoplus_{|\mu|=t+1,\ |\nu|=t+1}S_\mu(\Lambda^pA){\otimes}S_{\mu'}B^*{\otimes}S_\nu(\Lambda^{p+1}A^*){\otimes}S_{\nu'}C^*.$$

Determining which irreducible submodules of (6) actually contribute nontrivial equations appears to be difficult.

3. Proof of Theorem 1.1

Let M, N, L be vector spaces of dimensions $\mathbf{m}, \mathbf{n}, \mathbf{l}$. Write $A = M{\otimes}N^*$, $B = N{\otimes}L^*$, $C = L{\otimes}M^*$, so $\mathbf{a} = \mathbf{mn}$, $\mathbf{b} = \mathbf{nl}$, $\mathbf{c} = \mathbf{ml}$. The matrix multiplication operator $M_{<\mathbf{m},\mathbf{n},\mathbf{l}>}$ is $M_{<\mathbf{m},\mathbf{n},\mathbf{l}>} = Id_M{\otimes}Id_N{\otimes}Id_L \in A{\otimes}B{\otimes}C$. (See [9, §2.5.2] for an explanation of this identification.) Let $U = N^*$. Then

$$(M_{\langle\mathbf{m},\mathbf{n},\mathbf{l}\rangle})_A^{\wedge p} \colon L \otimes U {\otimes} \wedge^p (M{\otimes}U) \to L{\otimes}M^*{\otimes} \wedge^{p+1} (M{\otimes}U). \tag{7}$$

This is just the identity map on the L factor, so we may write $M^{\wedge p}_{\mathbf{m},\mathbf{n},\mathbf{l}} = \psi_p{\otimes}Id_L$, where

$$\psi_p : \Lambda^p(M{\otimes}U){\otimes}U \to M^*{\otimes}\Lambda^{p+1}(M{\otimes}U). \tag{8}$$

The essential idea is to choose a subspace $A' \subset M{\otimes}U$ on which the "restriction" of ψ_p becomes injective for $p = \mathbf{n}-1$. Take a vector space W of dimension 2, and fix isomorphisms $U \simeq S^{\mathbf{n}-1}W^*$, $M \simeq S^{\mathbf{m}-1}W^*$. Let A' be the $SL(W)$-direct summand $S^{\mathbf{m}+\mathbf{n}-2}W^* \subset S^{\mathbf{n}-1}W^*{\otimes}S^{\mathbf{n}-1}W^* = M{\otimes}U$.

Recall that $S^\alpha W$ may be interpreted as the space of homogenous polynomials of degree α in two variables. If $f \in S^\alpha W$ and $g \in S^\beta W^*$ (with $\beta \le \alpha$) then we can perform the contraction $g \cdot f \in S^{\alpha-\beta}W$. In the case $f = l^\alpha$ is the power of a linear form l, then the contraction $g \cdot l^\alpha$ equals $l^{\alpha-\beta}$ multiplied by the value of g at the point l, so that $g \cdot l^\alpha = 0$ if and only if l is a root of g.

Consider the natural skew-symmetrization map

$$A' \otimes \wedge^{\mathbf{n}-1}(A') \longrightarrow \wedge^{\mathbf{n}} (A'). \tag{9}$$

Because $SL(W)$ is reductive, there is a unique $SL(W)$-complement A'' to A', so the projection $M{\otimes}U \to A'$ is well defined. Compose (9) with the projection

$$M \otimes U \otimes \wedge^{\mathbf{n}-1}(A') \longrightarrow A' \otimes \wedge^{\mathbf{n}}(A') \tag{10}$$

to obtain

$$M \otimes U \otimes \wedge^{\mathbf{n}-1}(A') \longrightarrow \wedge^{\mathbf{n}} (A'). \tag{11}$$

Now (11) gives a map

$$\psi'_p : U \otimes \wedge^{\mathbf{n}-1}(A') \longrightarrow M^* \otimes \wedge^{\mathbf{n}}(A'). \tag{12}$$

We claim (12) is injective. (Note that when $\mathbf{n} = \mathbf{m}$ the source and target space of (12) are dual to each other.)

Consider the transposed map $S^{\mathbf{m}-1}W^*{\otimes} \wedge^{\mathbf{n}} S^{\mathbf{m}+\mathbf{n}-2}W \to S^{\mathbf{n}-1}W{\otimes} \wedge^{\mathbf{n}-1} S^{\mathbf{m}+\mathbf{n}-2}W$. It is defined as follows on decomposable elements (and then extended by linearity):

$$g{\otimes}(f_1 \wedge \cdots \wedge f_{\mathbf{n}}) \mapsto \sum_{i=1}^{\mathbf{n}} (-1)^{i-1} g(f_i){\otimes}f_1 \wedge \cdots \hat{f}_i \cdots \wedge f_{\mathbf{n}}$$

We show this dual map is surjective. Let $l^{\mathbf{n}-1}{\otimes}(l_1^{\mathbf{m}+\mathbf{n}-2} \wedge \cdots \wedge l_{\mathbf{n}-1}^{\mathbf{m}+\mathbf{n}-2}) \in S^{\mathbf{n}-1}W{\otimes} \wedge^{\mathbf{n}-1} S^{\mathbf{m}+\mathbf{n}-2}W$ with $l_i \in W$. Such elements span the target so it will be sufficient to show any such element is in the image. Assume first that l is distinct from the l_i. Since $\mathbf{n} \le \mathbf{m}$, there is a polynomial $g \in S^{\mathbf{m}-1}W^*$ which vanishes on $l_1, \ldots, l_{\mathbf{n}-1}$ and is nonzero on l. Then, up to a nonzero scalar, $g{\otimes}(l_1^{\mathbf{m}+\mathbf{n}-2} \wedge \cdots \wedge l_{\mathbf{n}-1}^{\mathbf{m}+\mathbf{n}-2} \wedge l^{\mathbf{m}+\mathbf{n}-2})$ maps to our element.

Since the image is closed (being a linear space), the condition that l is distinct from the l_i may be removed by taking limits.

Finally, $\psi'_p \otimes Id_L \colon B^* \otimes \wedge^{\mathbf{n}-1} A' \to C \otimes \wedge^{\mathbf{n}} A'$ is the map induced from the restricted matrix multiplication operator.

To complete the proof of Theorem 1.1, observe that an element of rank one in $A' \otimes B \otimes C$ induces a map $B^* \otimes \Lambda^{n-1} A' \to C \otimes \Lambda^n A'$ of rank $\binom{\mathbf{n}+\mathbf{m}-2}{\mathbf{n}-1}$.

By Lemma 3.1 below, the border rank of $M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle}$ must be at least the border rank of $T' \in A' \otimes B \otimes C$, and by Theorem 2.1

$$\underline{\mathbf{R}}(T') \geq \frac{\dim B^* \otimes \wedge^{\mathbf{n}-1}(A')}{\binom{\mathbf{n}+\mathbf{m}-2}{\mathbf{n}-1}} = \mathbf{nl}\frac{\binom{\mathbf{n}+\mathbf{m}-1}{\mathbf{n}-1}}{\binom{\mathbf{n}+\mathbf{m}-2}{\mathbf{n}-1}} = \frac{\mathbf{nl}\,(\mathbf{n}+\mathbf{m}-1)}{\mathbf{m}}.$$

This concludes the proof of Theorem 1.1.

Lemma 3.1. *Let $T \in A \otimes B \otimes C$, let $A = A' \oplus A''$ and let $\pi \colon A \to A'$ be the linear projection, which induces $\tilde{\pi} \colon A \otimes B \otimes C \to A' \otimes B \otimes C$. Then $\mathbf{R}(T) \geq \mathbf{R}(\tilde{\pi}(T))$ and $\underline{\mathbf{R}}(T) \geq \underline{\mathbf{R}}(\tilde{\pi}(T))$.*

Proof. If $T = \sum_{i=1}^r a_i \otimes b_i \otimes c_i$ then $\tilde{\pi}(T) = \sum_{i=1}^r \pi(a_i) \otimes b_i \otimes c_i$. □

Remark 3.2. If we let $B' = U$, $C' = M$, then in the proof above we are just computing the rank of $(T')^{\wedge p}_A$ where $T' \in A \otimes B' \otimes C'$ is $Id_U \otimes Id_M$. The maximal border rank of a tensor T in $\mathbb{C}^{\mathbf{mn}} \otimes \mathbb{C}^{\mathbf{m}} \otimes \mathbb{C}^{\mathbf{n}}$ is $\mathbf{mn}$ which occurs anytime the map $T : \mathbb{C}^{\mathbf{mn}*} \to \mathbb{C}^{\mathbf{m}} \otimes \mathbb{C}^{\mathbf{n}}$ is injective, so T' is a generic tensor in $A \otimes B' \otimes C'$, and the calculation of rank(ψ'_p) is determining the maximal rank of $(T')^{\wedge p}_A$ for a generic element of $\mathbb{C}^{\mathbf{mn}} \otimes \mathbb{C}^{\mathbf{n}} \otimes \mathbb{C}^{\mathbf{m}}$. Also note that the projection $A \to A'$, viewed as linear map $S^{\mathbf{n}-1}W^* \otimes S^{\mathbf{n}-1}W^* \to S^{\mathbf{m}+\mathbf{n}-2}W^*$ is just polynomial multiplication.

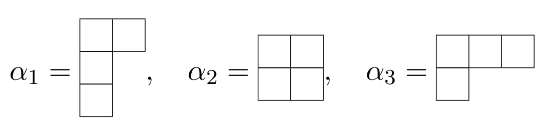
4. The kernel through representation theory

We compute the kernel of the map (4) as a module and give a formula for its dimension as an alternating sum of products of binomial coefficients. The purpose of this section is to show that there are nontrivial equations for tensors of border rank less than $2\mathbf{n}^2$ that matrix multiplication *does* satisfy, and to develop a description of the kernel that, we hope, will be useful for future research.

4.1. The kernel as a module.

Assume $\mathbf{b} \leq \mathbf{c}$, so $\mathbf{n} \leq \mathbf{m}$. For a partition $\pi = (\pi_1, \ldots, \pi_N)$, let $\ell(\pi)$ denote the number of parts of π, i.e., the largest k such that $\pi_k > 0$. Let π' denote the conjugate partition to π. See §6.1 for the definition of $S_\pi U$.

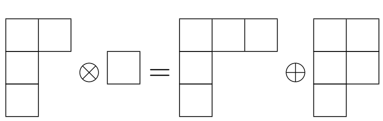
Example 4.1. Consider the case $\mathbf{m} = \mathbf{n} = 3$, take $p = 4$. Let

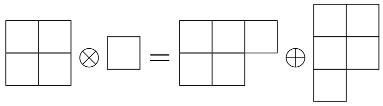


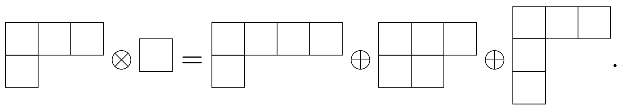
Note that $\alpha_1 = \alpha'_3$, $\alpha_2 = \alpha'_2$. Then (see §6.2)

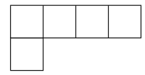
$$\wedge^4(M \otimes U) = (S_{\alpha_3}M \otimes S_{\alpha_1}U) \oplus (S_{\alpha_2}M \otimes S_{\alpha_2}U) \oplus (S_{\alpha_1}M \otimes S_{\alpha_3}U)\,.$$

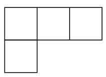
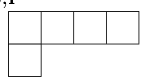
Observe that (via the Pieri rule §6.3)





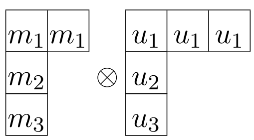


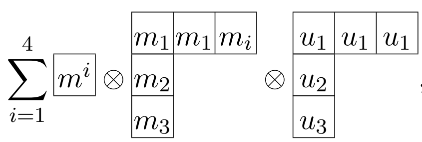
Among the seven summands on the right-hand side, only  does not fit in the 3×3 square. The kernel of $M^{\wedge 4}_{3,3,\mathbf{l}}$ in this case is $L^*{\otimes}S_{2,1,1}M{\otimes}S_{4,1}U$, corresponding to

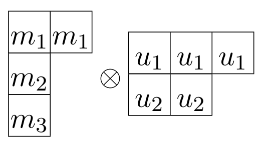
$\pi =$  $\pi + (1) =$  which has dimension $\mathbf{l} \cdot 24 \cdot 3 = 72\mathbf{l}$.

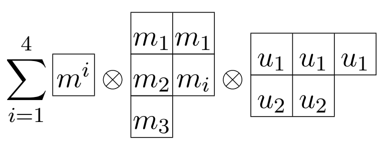
Let's show that the other two summands in $L^*{\otimes}S_{\alpha_1}M{\otimes}S_{\alpha_3}U{\otimes}U$, which are $L^*{\otimes}S_{2,1,1}M{\otimes}S_{3,1,1}U$ and $L^*{\otimes}S_{2,1,1}M{\otimes}S_{3,2}U$ are mapped to nonzero elements.

We have (forgetting the identity on L^*), the weight vector



going to , which is nonzero

and the weight vector  going to

 which is nonzero, too.

Hence the rank of $M^{\wedge 4}_{\langle 3,3,\mathbf{l}\rangle}$ is $3\mathbf{l} \cdot \binom{9}{4} - 72\mathbf{l} = 306\mathbf{l}$ and $\underline{\mathbf{R}}(M_{\langle 3,3,\mathbf{l}\rangle}) \geq \lceil \frac{306\mathbf{l}}{\binom{8}{4}} \rceil = \lceil \frac{306\mathbf{l}}{70} \rceil$ which coincides with Lickteig's bound of 14 when $\mathbf{l} = 3$.

Lemma 4.2. $\ker(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle})^{\wedge p}_A = \oplus_\pi S_{\pi'}M{\otimes}S_{\pi+(1)}U{\otimes}L$ *where the summation is over partitions* $\pi = (\mathbf{m}, \nu_1, \ldots, \nu_{\mathbf{n}-1})$ *where* $\nu = (\nu_1, \ldots, \nu_{\mathbf{n}-1})$ *is a partition of* $p - \mathbf{m}$*,* $\nu_1 \leq \mathbf{m}$ *and* $\pi + (1) = (\mathbf{m}+1, \nu_1, \ldots, \nu_{\mathbf{n}-1})$*.*

Proof. Write $M^{\wedge p}_{\mathbf{m},\mathbf{n},\mathbf{l}} = \psi_p{\otimes}Id_L$, where $\psi_p : \Lambda^p(M{\otimes}U){\otimes}U \to M^*{\otimes}\Lambda^{p+1}(M{\otimes}U)$. Such modules are contained in the kernel by Schur's lemma, as there is no corresponding module in the target for it to map to

We show that all other modules in $\Lambda^p(M{\otimes}U){\otimes}U$ are not in the kernel by computing ψ_p at weight vectors. Set $T' = Id_U{\otimes}Id_M$, so $\psi_p = (T')^{\wedge p}_A$. Write $T' = (u^i{\otimes}m_\alpha){\otimes}m^\alpha{\otimes}u_i$, where $1 \leq i \leq \mathbf{n}$, $1 \leq \alpha \leq \mathbf{m}$, (u^i) is the dual basis to (u_i) and similarly for (m^α) and (m_α), and the summation convention is used throughout. Then

$$T'{\otimes}Id_{\Lambda^p A} = (u^i{\otimes}m_\alpha){\otimes}m^\alpha{\otimes}u_i{\otimes}[(u_{j_1}{\otimes}m^{\beta_1}) \wedge \cdots \wedge (u_{j_p}{\otimes}m^{\beta_p})]{\otimes}[(u^{j_1}{\otimes}m_{\beta_1}) \wedge \cdots \wedge (u^{j_p}{\otimes}m_{\beta_p})]$$

and

$$(T')^{\wedge p}_A = [(u_{j_1}\otimes m^{\beta_1})\wedge\cdots\wedge(u_{j_p}\otimes m^{\beta_p})]\otimes u_i \bigotimes m^{\alpha}\otimes[(u^{j_1}\otimes m_{\beta_1})\wedge\cdots\wedge(u^{j_p}\otimes m_{\beta_p})\wedge(u^i\otimes m_{\alpha})]$$

Note that all the summands of the decomposition (see (18)) $\Lambda^p(M\otimes U)=\oplus_{|\alpha|=p}(S_\alpha M\otimes S_{\alpha'}U)$ are multiplicity free, it follows that also the summands of $\Lambda^p(M\otimes U)\otimes U$ are multiplicity free. So we can compute $(T')^{\wedge p}_A$ considering one weight vector for any irreducible summand. Under the mapping of a weight vector, nothing happens to the U component. The M component gets tensored with the identity map and then projected onto the component that gives the conjugate diagram to the one of U. So it just remains to see this projection is nonzero. But the projection is just as in Example 4.1, we add a box in the appropriate place and sum over basis vectors. Since the diagram will be one that produces a nonzero module for M, at least one basis vector can be placed in the new box to yield a nonzero Young tableaux. But we are summing over all basis vectors. □

4.2. **Dimension of the kernel.** We compute the dimension of $\ker(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle})^{\wedge p}_A=\ker\psi_p\otimes Id_L$ via an exact sequence. We continue the notations of above. Consider the map

$$\psi_{p,2}:\Lambda^{p-\mathbf{m}}(M\otimes U)\otimes\Lambda^{\mathbf{m}}M\otimes S^{\mathbf{m}+1}U\to\Lambda^p(M\otimes U)\otimes U \tag{13}$$

$$T\otimes m_1\wedge\cdots\wedge m_{\mathbf{m}}\otimes u^{\mathbf{m}+1}\mapsto T\wedge(m_1\otimes u)\wedge\cdots\wedge(m_{\mathbf{m}}\otimes u)\otimes u. \tag{14}$$

Lemma 4.3. Image $\psi_{p,2}=\ker\psi_p$.

Proof. Observe that

$$\psi_p:\bigoplus_{\substack{|\pi|=p,\ell(\pi)\le\mathbf{n}\\ \pi_1\le\mathbf{m}}} S_\pi U\otimes U\otimes S_{\pi'}M\to\bigoplus_{\substack{|\mu|=p+1,\ell(\mu)\le\mathbf{m}\\ \mu_1\le\mathbf{n}}} S_\mu M\otimes M^*\otimes S_{\mu'}U$$

is a $GL(U)\times GL(M)$-module map. Now the source of $\psi_{p,2}$ is

$$\bigoplus_{\substack{|\nu|=p-\mathbf{m},\nu_1\le\mathbf{m}\\ \ell(\nu)\le\mathbf{n}}} S_{\nu'}M\otimes S_\nu U\otimes S^{\mathbf{m}+1}U\otimes\Lambda^{\mathbf{m}}M$$

and a given module in the source with $\nu_{\mathbf{n}}=0$ maps to $S_{\pi+(1)}U\otimes S_{\pi'}M\subset S_\pi U\otimes U\otimes S_{\pi'}M$ where $\pi=(\mathbf{m},\nu_1,\dots,\nu_{\mathbf{n}-1})$, the proof is similar to the proof of Lemma 4.2. Its other components map to zero. □

The kernel of $\psi_{p,2}$ is the image of

$$\begin{aligned}\psi_{p,3}:\Lambda^{p-\mathbf{m}-1}(M\otimes U)\otimes\Lambda^{\mathbf{m}}M\otimes M\otimes S^{\mathbf{m}+2}U&\to\Lambda^{p-\mathbf{m}}(M\otimes U)\otimes\Lambda^{\mathbf{m}}M\otimes S^{\mathbf{m}+1}U\\ T\otimes m_1\wedge\cdots\wedge m_{\mathbf{m}}\otimes m\otimes u^{\mathbf{m}+2}&\mapsto T\wedge(m\otimes u)\otimes m_1\wedge\cdots\wedge m_{\mathbf{m}}\otimes u^{\mathbf{m}+1}\end{aligned}\tag{15}$$

and $\psi_{p,3}$ has kernel the image of

$$\begin{aligned}\psi_{p,4}:\Lambda^{p-\mathbf{m}-2}(M\otimes U)\otimes\Lambda^{\mathbf{m}}M\otimes S^2M\otimes S^{\mathbf{m}+3}U&\to\Lambda^{p-\mathbf{m}-1}(M\otimes U)\otimes\Lambda^{\mathbf{m}}M\otimes M\otimes S^{\mathbf{m}+2}U\\ T\otimes m_1\wedge\cdots\wedge m_{\mathbf{m}}\otimes m^2\otimes u^{\mathbf{m}+3}&\mapsto T\wedge(m\otimes u)\otimes m_1\wedge\cdots\wedge m_{\mathbf{m}}\otimes m\otimes u^{\mathbf{m}+2}\end{aligned}\tag{16}$$

One defines analogous maps $\psi_{p,k}$. By taking the Euler characteristic we obtain:

Lemma 4.4.

$$\dim\ker\psi_p=\sum_{j=0}^{p-\mathbf{m}}(-1)^j\binom{\mathbf{mn}}{p-\mathbf{m}-j}\binom{\mathbf{m}+j-1}{j}\binom{\mathbf{m}+\mathbf{n}+j}{\mathbf{m}+j+1}.$$

In summary:

Theorem 4.5. *Set* $p \le \lceil \frac{\mathbf{mn}}{2} \rceil - 1$ *and assume* $\mathbf{n} \le \mathbf{m}$. *Then*

$$\dim(\ker(M_{\langle \mathbf{m},\mathbf{n},\mathbf{l}\rangle})_A^{\wedge p}) = \mathbf{l} \sum_{j=0}^{p-\mathbf{m}} (-1)^j \binom{\mathbf{mn}}{p-\mathbf{m}-j} \binom{\mathbf{m}+j-1}{j} \binom{\mathbf{m}+\mathbf{n}+j}{\mathbf{m}+j+1}.$$

In the case $\mathbf{m} = \mathbf{n}$ one can get a smaller kernel by identifying $V^* \simeq U$ and restricting to $A' = S^2 U \subset U \otimes U$, although this does not appear to give a better lower bound than Theorem 1.2. A different restriction that allows for a small kernel could conceivably give a better bound.

5. Review of Lickteig's bound

For comparison, we outline the proof of Lickteig's bound. (Expositions of Strassen's bound are given in several places, e.g. [9, Chap. 3] and [3, §19.3].) It follows in three steps. The first combines two standard facts from algebraic geometry: for varieties $X, Y \subset \mathbb{P}V$, let $J(X,Y) \subset \mathbb{P}V$ denote the join of X and Y. Then $\sigma_{r+s}(X) = J(\sigma_r(X), \sigma_s(X))$. If $X = Seg(\mathbb{P}A \times \mathbb{P}B \times \mathbb{P}C)$ is a Segre variety, then $\sigma_s(Seg(\mathbb{P}A \times \mathbb{P}B \times \mathbb{P}C)) \subseteq Sub_s(A \otimes B \otimes C)$, where

$$Sub_s(A\otimes B\otimes C) := \{T \in A\otimes B\otimes C \mid \exists A' \subset A,\ B' \subset B, C' \subset C,\ \dim A' = \dim B' = \dim C' = s,\ T \in A'\otimes B'\otimes C'\}.$$

See, e.g.,[9, §7.1.1] for details. Next Lickteig observes that if $T \in \sigma_{r+s}(Seg(\mathbb{P}A \times \mathbb{P}B \times \mathbb{P}C))$, then there exist A', B', C' each of dimension s such that, thinking of $T : A^* \otimes B^* \to C$,

$$\dim(T((A')^{\perp} \otimes B^* + A^* \otimes (B')^{\perp})) \le r. \tag{17}$$

This follows because the condition is a closed condition and it holds for points on the open subset of points in the span of $r + s$ points on $Seg(\mathbb{P}A \times \mathbb{P}B \times \mathbb{P}C)$.

Finally, for matrix multiplication, with $A = M \otimes N^*$ etc., he defines $M' \subset M$, $N^{*\prime} \subset N^*$ to be the smallest spaces such that $A' \subseteq M' \otimes N^{*\prime}$ and similarly for the other spaces. Then one applies (17) combined with the observation that $M|_{(A')^{\perp} \otimes B^*} \subseteq M' \otimes L^*$ etc., and keeps track of the various bounds to conclude.

6. Appendix: facts from representation theory

6.1. **Representations of** $GL(V)$**.** The irreducible representations of $GL(V)$ are indexed by sequences $\pi = (p_1, \dots, p_l)$ of non-increasing integers with $l \le \dim V$. Those that occur in $V^{\otimes d}$ are partitions of d, and we write $|\pi| = d$ and $S_\pi V$ for the module. $V^{\otimes d}$ is also an $\mathfrak{S}_d$-module, and the groups $GL(V)$ and $\mathfrak{S}_d$ are the commutants of each other in $V^{\otimes d}$ which implies the famous Schur-Weyl duality that $V^{\otimes d} = \oplus_{|\pi|=d, \ell(\pi) \le \mathbf{v}} S_\pi V \otimes [\pi]$ as a $(GL(V) \times \mathfrak{S}_d)$-module, where $[\pi]$ is the irreducible $\mathfrak{S}_d$-module associated to π. Repeated numbers in partitions are sometimes expressed as exponents when there is no danger of confusion, e.g. $(3,3,1,1,1,1) = (3^2, 1^4)$. For example, $S_{(d)}V = S^d V$ and $S_{(1^d)}V = \Lambda^d V$. The modules $S_{s^{\mathbf{v}}}V = (\Lambda^{\mathbf{v}} V)^{\otimes s}$ are trivial as $SL(V)$-modules . The module $S_{(22)}V$ is the home of the Riemann curvature tensor in Riemannian geometry. See any of [9, Chap. 6], [4, Chap 6] or [15, Chap. 9] for more details on the representations of $GL(V)$ and what follows.

6.2. **Useful decomposition formulas.** To decompose $S^2(A \otimes B)$ as a $GL(A) \times GL(B)$-module, note that given $P \in S^2 A$ and $Q \in S^2 B$, the product of P and Q defined by $P \otimes Q(\alpha \otimes \beta, \alpha' \otimes \beta') := P(\alpha, \alpha') Q(\beta, \beta')$ will be in $S^2(A \otimes B)$. Similarly, if $P \in \Lambda^2 A$ and $Q \in \Lambda^2 B$, $P \otimes Q$ will also be symmetric as $P(\alpha', \alpha) Q(\beta', \beta) = [-P(\alpha, \alpha')][-Q(\beta, \beta')] = P(\alpha, \alpha') Q(\beta, \beta')$. Since the dimensions of these spaces add to the dimension of $S^2(A \otimes B)$ we conclude

$$S^2(A \otimes B) = (S^2 A \otimes S^2 B) \oplus (\Lambda^2 A \otimes \Lambda^2 B).$$

By an analogous argument, we have the decomposition

$$\Lambda^2(A \otimes B) = (S^2 A \otimes \Lambda^2 B) \oplus (\Lambda^2 A \otimes S^2 B).$$

More generally (see, e.g. [9, §6.5.2]) we have

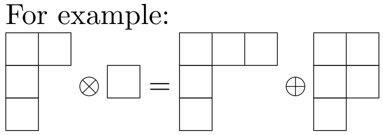
$$\Lambda^p(A \otimes B) = \oplus_{|\pi|=p} S_\pi A \otimes S_{\pi'} B \tag{18}$$

$$S^p(A \otimes B) = \oplus_{|\pi|=p} S_\pi A \otimes S_\pi B \tag{19}$$

where π' denotes the conjugate partition to π, that is, if we represent $\pi = (p_1, \dots, p_n)$ by a Young diagram, with p_j boxes in the j-th row, the diagram of π' is obtained by reflecting the diagram of π along the NW to SE axis.

6.3. **The Pieri rule.** The decomposition of $S_\pi V \otimes V$ is multiplicity free, consisting of a copy of each $S_\mu V$ such that the Young diagram of μ is obtained from the Young diagram of π by adding a box. (Boxes must be added in such a way that one still has a partition and the number of rows is at most the dimension of V.)

For example:



More generally, *Pieri formula* states that $S_\pi V \otimes S^d V$ decomposes multiplicity free into the sum of all $S_\mu V$ that can be obtained by adding d boxes to the Young diagram of π in such a way that no two boxes are added to the same column, and $S_\pi V \otimes \Lambda^d V$ decomposes multiplicity free into the sum of all $S_\mu V$ that can be obtained by adding d boxes to the Young diagram of π in such a way that no two boxes are added to the same row. See any of the standard references given above for details.

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E-mail address: `jml@math.tamu.edu, ottavian@math.unifi.it`