

# Kronecker coefficients: the tensor square conjecture and unimodality

Igor Pak, Greta Panova, Ernesto Vallejo

► **To cite this version:**

Igor Pak, Greta Panova, Ernesto Vallejo. Kronecker coefficients: the tensor square conjecture and unimodality. Louis J. Billera and Isabella Novik. 26th International Conference on Formal Power Series and Algebraic Combinatorics (FPSAC 2014), 2014, Chicago, United States. Discrete Mathematics and Theoretical Computer Science, DMTCS Proceedings vol. AT, 26th International Conference on Formal Power Series and Algebraic Combinatorics (FPSAC 2014), pp.149-160, 2014, DMTCS Proceedings. <hal-01207577>

**HAL Id: hal-01207577**

**<https://hal.inria.fr/hal-01207577>**

Submitted on 1 Oct 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Kronecker coefficients: the tensor square conjecture and unimodality

Igor Pak<sup>1\*</sup>Greta Panova<sup>1†</sup>Ernesto Vallejo<sup>2‡</sup><sup>1</sup>University of California Los Angeles, USA<sup>2</sup>Centro de Ciencias Matemáticas, Universidad Nacional Autónoma de México, Morelia, Mexico

**Abstract.** We consider two aspects of Kronecker coefficients in the directions of representation theory and combinatorics. We consider a conjecture of Jan Saxl stating that the tensor square of the  $S_n$ -irreducible representation indexed by the staircase partition contains every irreducible representation of  $S_n$ . We present a sufficient condition allowing to determine whether an irreducible representation is a constituent of a tensor square and using this result together with some analytic statements on partitions we prove Saxl conjecture for several partition classes. We also use Kronecker coefficients to give a new proof and a generalization of the unimodality of Gaussian ( $q$ -binomial) coefficients as polynomials in  $q$ , and extend this to strict unimodality.

**Résumé.** Nous considérons deux aspects des coefficients de Kronecker dans le domaine de la Théorie des Représentations et le domaine Combinatoire. Nous considérons la conjecture suivante de Jan Saxl: le tenseur au carré de la représentation irréductible du groupe  $S_n$  indexée par la partition  $(k, k-1, \dots, 1)$  contient toutes les représentations irréductibles du groupe  $S_n$  ( $n = \binom{k+1}{2}$ ). Nous présentons une condition suffisante qui permet de déterminer si une représentation irréductible est une constituante d'un tenseur au carré. En utilisant ce résultat avec des résultats analytiques sur les partitions, nous prouvons la conjecture de Saxl pour plusieurs classes de partitions. Nous utilisons aussi les coefficients de Kronecker pour donner une nouvelle preuve et une généralisation de l'unimodalité des coefficients de Gauss ( $q$ -binomiaux) comme polynômes en  $q$  et nous étendons cela à l'unimodalité stricte.

**Keywords:** Kronecker coefficients, symmetric group, irreducible representations, tensor square, unimodality, integer partitions, Gaussian coefficients

## 1 Introduction

The *Kronecker product problem* is a problem of computing the multiplicities, called Kronecker coefficients,

$$g(\lambda, \mu, \nu) = \langle \chi^\lambda, \chi^\mu \otimes \chi^\nu \rangle$$

of an irreducible character of  $S_n$  in the tensor product of two others. These coefficients and the problem were introduced 75 years ago by Murnaghan following the discovery of the Littlewood-Richardson rule. It

\*Email: pak@math.ucla.edu. Partially supported by BSF and NSF grant.

†Email: panova@math.ucla.edu. Partially supported by a Simons Postdoctoral Fellowship.

‡Email: vallejo@matmor.unam.mx. Supported by DGAPA-UNAM grants IN-102611 and IN-108314.

is often referred as “classic”, and “one of the last major open problems” in algebraic combinatorics [BWZ, Reg]. The significance of Kronecker coefficients has recently found a new meaning in Complexity Theory via a program designed to prove the “P vs NP” problem (see e.g. [Mul, MNS, MS]). Despite a large body of work on the Kronecker coefficients, both classical and very recent (see e.g. [BO2, Bla, BOR, Ike, Reg, Rem, RW, Val1, Val2] and references therein), it is universally agreed that “frustratingly little is known about them” [Bür]. Most results are limited to partitions of very specific shapes (when one of the partitions  $\lambda, \mu, \nu$  is a hook or two row with further restrictions) and are far from answering the natural questions that arise. We now present two problems, one of representation theoretic and another of combinatorial nature, where we develop some tools and consider new aspects of this old problem. The work presented in this abstract is based on the results from [PPV], [PP-u], [PP-s], and partially on [Val3].

### 1.1 The tensor square conjecture

Motivated by *John Thompson’s conjecture* and *Passman’s problem*, Heide, Saxl, Tiep and Zalesski recently proved that with a few known exceptions, every irreducible character of a simple group of Lie type is a constituent of the tensor square of the Steinberg character [HSTZ]. They conjecture that for every  $n \geq 5$ , there is an irreducible character  $\chi$  of  $A_n$  whose tensor square  $\chi \otimes \chi$  contains every irreducible character as a constituent.<sup>(i)</sup> Here is the symmetric group analogue of this conjecture:

**Conjecture 1.1 (Tensor square conjecture)** *For every  $n \geq 3$ ,  $n \neq 4, 9$ , there is a partition  $\mu \vdash n$ , such that tensor square of the irreducible character  $\chi^\mu$  of  $S_n$  contains every irreducible character as a constituent.*

During a talk at UCLA, Jan Saxl made the following conjecture, somewhat refining the tensor square conjecture.<sup>(ii)</sup>

**Conjecture 1.2 (Saxl conjecture)** *Denote by  $\rho_k = (k, k-1, \dots, 2, 1) \vdash n$ , where  $n = \binom{k+1}{2}$ . Then for every  $k \geq 1$ , the tensor square  $\chi^{\rho_k} \otimes \chi^{\rho_k}$  contains every irreducible character of  $S_n$  as a constituent.*

Andrew Soffer checked the validity of this conjecture for  $k \leq 8$ .<sup>(iii)</sup> While we believe the conjecture, we also realize that it is beyond the reach of current technology. More importantly, we develop a new tool, aimed specifically at the Saxl conjecture, which gives a positivity criterion for Kronecker coefficients:

**Lemma 1.3 (Main Lemma)** *Let  $\mu = \mu'$  be a self-conjugate partition of  $n$ , and let  $\hat{\mu} = (2\mu_1 - 1, 2\mu_2 - 3, 2\mu_3 - 5, \dots) \vdash n$  be the partition whose parts are lengths of the principal hooks of  $\mu$ . Suppose  $\chi^\lambda[\hat{\mu}] \neq 0$  for some  $\lambda \vdash n$ . Then  $\chi^\lambda$  is a constituent of  $\chi^\mu \otimes \chi^\mu$ .*

We use this lemma together with analytic results on the growth of certain partition functions to obtain the following technical results (among others) towards Saxl Conjecture.

**Theorem 1.4** *There is a universal constant  $L$ , such that for every  $k \geq L$ , the tensor square  $\chi^{\rho_k} \otimes \chi^{\rho_k}$  contains characters  $\chi^\lambda$  as constituents, for all*

$$\begin{aligned} \lambda = (n - \ell, \ell), \quad 0 \leq \ell \leq n/2, \quad \lambda = (n - r, 1^r), \quad 0 \leq r \leq n - 1, \\ \lambda = (n - \ell - m, \ell, m), \quad m \in \{1, 3, 5, 7, 8, 9\}, \quad L \leq \ell + m \leq n/2, \end{aligned}$$

<sup>(i)</sup> Authors of [HSTZ] report that this conjecture was checked by Eamonn O’Brien for  $n \leq 17$ .

<sup>(ii)</sup> UCLA Combinatorics Seminar, Los Angeles, March 20, 2012.

<sup>(iii)</sup> Personal communication.

$$\text{or } \lambda = (n - r - m, m, 1^r), \quad 1 \leq m \leq 10, L \leq r < n/2 - 5.$$

These results are based on the work in [PPV], we present some of them here.

## 1.2 Unimodality via Kronecker coefficients

A sequence  $(a_1, a_2, \dots, a_n)$  is called *unimodal*, if for some  $k$  we have

$$a_1 \leq a_2 \leq \dots \leq a_k \geq a_{k+1} \geq \dots \geq a_n.$$

The study of unimodality of combinatorial sequences is a classical subject going back to Newton, and has intensified in recent decades. There is a remarkable diversity of applicable tools, ranging from analytic to topological, and from representation theory to probabilistic analysis. The results have a number of application, but are also important in their own right. We refer to [B1, B2, Sta1] for a broad overview of the subject.

We present two extensions of the following classical unimodality result. The *q-binomial* (Gaussian) coefficients are defined as:

$$\binom{m+\ell}{m}_q = \frac{(q^{m+1}-1) \cdots (q^{m+\ell}-1)}{(q-1) \cdots (q^\ell-1)} = \sum_{n=0}^{\ell m} p_n(\ell, m) q^n.$$

Recall that  $p_n(\ell, m) = \#\mathcal{P}_n(\ell, m)$ , where  $\mathcal{P}_n(\ell, m)$  is the set of partitions  $\alpha \vdash n$ , such that  $\alpha_1 \leq m$  and  $\alpha'_1 \leq \ell$ . The unimodality of a sequence

$$p_0(\ell, m), p_1(\ell, m), \dots, p_{\ell m}(\ell, m)$$

is a celebrated result first conjectured by Cayley in 1856, and proved by Sylvester in 1878 [Syl] (see also [S1]). Historically, it has been a starting point of many investigations and various generalizations, both of combinatorial and algebraic nature. The original proof of this result by Sylvester relies on an intricate use of Lie algebras. Subsequent proofs were given by Stanley [S2] and Proctor [Pro] which are also algebraic. The only known combinatorial proof of the unimodality of *q*-binomial coefficients is given by O'Hara in [O'H] (see also [SZ, Zei]). However, O'Hara's construction does not give a symmetric chain decomposition of the poset  $L(\ell, m)$  of partitions which fit the  $\ell \times m$  rectangle (in other words, the difference between successive partitions is not always a corner). Existence of such decompositions remains an open problem (see e.g. [S2, Wen] and references therein).

Denote by  $v(\alpha)$  the number of distinct part sizes in the partition  $\alpha$ . The sequence  $(a_1, \dots, a_n)$  is called *symmetric* if  $a_i = a_{n+1-i}$ , for all  $i \leq i \leq n$ .

Using Kronecker coefficients we prove in [PP-u] the following extension of Sylvester's theorem.

**Theorem 1.5** *Let*

$$p_n(\ell, m, r) = \sum_{\alpha \in \mathcal{P}_n(\ell, m)} \binom{v(\alpha)}{r}.$$

*Then the sequence*

$$p_r(\ell, m, r), p_{r+1}(\ell, m, r), \dots, p_{\ell m}(\ell, m, r)$$

*is symmetric and unimodal.*

Note that  $p_n(\ell, m, r) = 0$  for  $n < \binom{r+1}{2}$  or  $n > \ell m - \binom{r}{2}$ , and that  $v(\alpha)$  can be viewed as the *number of corners* of the corresponding Young diagram  $[\alpha]$ . Moreover,  $p_n(\ell, m, 0) = p_n(\ell, m)$  and therefore, for  $r = 0$ , Theorem 1.5 gives the unimodality of  $q$ -binomial coefficients, and hence a new (up to our knowledge) proof of Sylvester's theorem. Moreover, the other known algebraic proofs do not imply such results. The chain construction argument from O'Hara's combinatorial proof also does not seem to imply Theorem 1.5 even in the case  $r = 1$ . Indeed, the value of  $v(\alpha)$  is not unimodal on the chains. For example, the fourth chain on p. 50 in [O'H] is

$$(2^2) \rightarrow (32) \rightarrow (42) \rightarrow (43) \rightarrow (43) \rightarrow (4^2) \rightarrow (4^21) \rightarrow (4^22) \rightarrow (4^23) \rightarrow (4^3),$$

and the number of corners dips in the middle. It would be interesting to find a combinatorial proof of the Theorem 1.5, which might lead to a way of finding a symmetric chain decomposition of the poset  $L(m, \ell)$  mentioned above. <sup>(iv)</sup>

We also use the recently established *semigroup property* of Kronecker coefficients to prove in [PP-s] *strict unimodality* of  $q$ -binomial coefficients:

**Theorem 1.6** *For all  $\ell, m \geq 8$ , we have the following strict inequalities:*

$$(\circ) \quad p_1(\ell, m) < \dots < p_{\lfloor \ell m/2 \rfloor}(\ell, m) = p_{\lceil \ell m/2 \rceil}(\ell, m) > \dots > p_{\ell m-1}(\ell, m).$$

The fact that strict unimodality of  $q$ -binomial coefficients was open until now is perhaps a reflection on the lack of analytic proof of Sylvester's theorem, as all known proofs are either algebraic or combinatorial (see [Pro, Stal]). <sup>(v)</sup>

## 2 A positivity criterion for $g(\mu, \mu, \lambda)$

**Lemma 1.3 (Main Lemma)** *Let  $\lambda, \mu \vdash n$ , such that  $\mu = \mu'$  and  $\chi^\lambda[\widehat{\mu}] \neq 0$ , where  $\widehat{\mu} = (2\mu_1 - 1, 2\mu_2 - 3, \dots)$ . Then  $g(\mu, \mu, \lambda) > 0$ .*

**Proof:** Let

$$\varepsilon_\mu = \chi^\mu[\widehat{\mu}] = (-1)^{(n-d(\mu))/2}.$$

The second equality follows from the Murnaghan-Nakayama rule, realizing that there is a unique way of fitting ribbons of size  $2\mu_1 - 1, \dots$  in the Young diagram of  $\mu$ . Recall also that the  $S_n$  conjugacy class of cycle type  $\zeta$ , when  $\zeta$  is a partition into distinct odd parts, splits into two conjugacy classes in the alternating group  $A_n$ , which we denote by  $\zeta^1$  and  $\zeta^2$ . There are two kinds of irreducible characters of  $A_n$ . For each partition  $\nu$  of  $n$  such that  $\nu = \nu'$  there are two irreducible characters associated to  $\nu$ , which we denote by  $\alpha^{\nu^+}$  and  $\alpha^{\nu^-}$ ; and for each partition  $\nu$  of  $n$  such that  $\nu \neq \nu'$  there is an irreducible character associated to the pair  $\nu, \nu'$ , which we denote by  $\alpha^\nu$ . These characters are related to irreducible characters of  $S_n$  as indicated below. We will need the following standard results (see e.g. [JK, Section 2.5]).

1. If  $\nu \neq \nu'$ , then

$$\text{Res}_{A_n}^{S_n}(\chi^\nu) = \text{Res}_{A_n}^{S_n}(\chi^{\nu'}) = \alpha^\nu,$$

<sup>(iv)</sup> Since then, a combinatorial proof relying on Sylvester's original result was given by J. Shareshian (personal communication), but without further insight into the structure of  $L(m, \ell)$ .

<sup>(v)</sup> New proofs using elementary methods like the KOH identity ([Zei]) have been found since [PP-s], see [Dh, Zan].

is an irreducible character of  $A_n$ .

2. If  $\nu = \nu'$ , then

$$\text{Res}_{A_n}^{S_n}(\chi^\nu) = \alpha^{\nu^+} + \alpha^{\nu^-},$$

is the sum of two different irreducible characters of  $A_n$ . Moreover, both characters are conjugate, that is, for any  $\sigma \in A_n$  we have

$$\alpha^{\nu^+}[(12)\sigma(12)] = \alpha^{\nu^-}[\sigma].$$

3. The characters  $\alpha^\nu$ ,  $\nu \neq \nu'$  and  $\alpha^{\nu^+}$ ,  $\alpha^{\nu^-}$ , where  $\nu = \nu'$  are all different and form a complete set of irreducible characters of  $A_n$ .

4. If  $\nu = \nu'$ , and  $\gamma$  is a conjugacy class of  $A_n$  different from  $\widehat{\nu}^1$  or  $\widehat{\nu}^2$ , then

$$\alpha^{\nu^+}[\gamma] = \alpha^{\nu^-}[\gamma] = \frac{1}{2} \chi^\nu[\gamma].$$

We also have

$$\begin{aligned} \alpha^{\nu^+}[\widehat{\nu}^1] &= \alpha^{\nu^-}[\widehat{\nu}^2] = \frac{1}{2} \left( \varepsilon_\nu + \sqrt{\varepsilon_\nu \prod_i \widehat{\nu}_i} \right), \\ \alpha^{\nu^+}[\widehat{\nu}^2] &= \alpha^{\nu^-}[\widehat{\nu}^1] = \frac{1}{2} \left( \varepsilon_\nu - \sqrt{\varepsilon_\nu \prod_i \widehat{\nu}_i} \right). \end{aligned}$$

In other words, for any self-conjugate partition  $\nu$ , the only irreducible characters of  $A_n$  that differ on the classes  $\widehat{\nu}^1$  and  $\widehat{\nu}^2$  are precisely  $\alpha^{\nu^\pm}$ .

There are two cases to consider with respect to whether  $\lambda$  is self-conjugate or not.

First, assume that  $\lambda \neq \lambda'$ . Then  $\alpha^\lambda$  is an irreducible character of  $A_n$ . Since

$$\alpha^\lambda[\widehat{\mu}^1] = \alpha^\lambda[\widehat{\mu}^2] = \chi^\lambda[\widehat{\mu}],$$

we obtain:

$$\begin{aligned} (\alpha^{\mu^+} \otimes \alpha^\lambda)[\widehat{\mu}^1] - (\alpha^{\mu^+} \otimes \alpha^\lambda)[\widehat{\mu}^2] &= (\alpha^{\mu^+}[\widehat{\mu}^1] - \alpha^{\mu^+}[\widehat{\mu}^2]) \cdot \chi^\lambda[\widehat{\mu}] \\ &= \left( \sqrt{\varepsilon_\mu \prod_i \widehat{\mu}_i} \right) \cdot \chi^\lambda(\widehat{\mu}) \neq 0. \end{aligned}$$

Therefore, either  $\alpha^{\mu^+}$  or  $\alpha^{\mu^-}$  is a component of  $\alpha^{\mu^+} \otimes \alpha^\lambda$ . In other words,

$$\text{either } \langle \alpha^{\mu^+} \otimes \alpha^\lambda, \alpha^{\mu^+} \rangle \neq 0 \quad \text{or} \quad \langle \alpha^{\mu^+} \otimes \alpha^\lambda, \alpha^{\mu^-} \rangle \neq 0.$$

We claim that the terms in these product can be interchanged. Formally, we claim that:

$$(\star) \quad \text{either } \langle \alpha^{\mu^+} \otimes \alpha^{\mu^+}, \alpha^\lambda \rangle \neq 0 \quad \text{or} \quad \langle \alpha^{\mu^+} \otimes \alpha^{\mu^-}, \alpha^\lambda \rangle \neq 0.$$

There are two cases. If  $\varepsilon_\mu = 1$ , then both  $\alpha^{\mu^+}$  and  $\alpha^{\mu^-}$  take real values. Thus

$$\langle \alpha^{\mu^+} \otimes \alpha^{\mu^\pm}, \alpha^\lambda \rangle = \langle \alpha^{\mu^+} \otimes \alpha^\lambda, \alpha^{\mu^\pm} \rangle \neq 0,$$

which implies  $(\star)$  in this case.

If  $\varepsilon_\mu = -1$ , then

$$\operatorname{Im}(\alpha^{\mu^+}[\widehat{\mu}^1]) = -\operatorname{Im}(\alpha^{\mu^-}[\widehat{\mu}^1]) \quad \text{and} \quad \operatorname{Im}(\alpha^{\mu^+}[\widehat{\mu}^2]) = -\operatorname{Im}(\alpha^{\mu^-}[\widehat{\mu}^2]).$$

Therefore,  $\overline{\alpha^{\mu^+}} = \alpha^{\mu^-}$ , since all other character values are real. Thus,

$$\langle \alpha^{\mu^+} \otimes \alpha^{\mu^\pm}, \alpha^\lambda \rangle = \langle \alpha^{\mu^+} \otimes \alpha^\lambda, \alpha^{\mu^\mp} \rangle \neq 0,$$

which implies  $(\star)$  in this case.

In summary, we have both cases in  $(\star)$  imply that  $\alpha^\lambda$  is a component of  $\operatorname{Res}_{A_n}^{S_n}(\chi^\mu \otimes \chi^\mu)$ . Therefore, either  $\chi^\lambda$  or  $\chi^{\lambda'}$  is a component of  $\chi^\mu \otimes \chi^\mu$ . Since  $\mu = \mu'$ , we have, since  $g(\mu, \mu, \lambda) = g(\mu, \mu, \lambda')$ , that  $\chi^\lambda$  and  $\chi^{\lambda'}$  are components of  $\chi^\mu \otimes \chi^\mu$ , as desired. This completes the proof of the  $\lambda \neq \lambda'$  case.

Now, suppose  $\lambda = \lambda'$ . The case  $\lambda = \mu$  is given in a Theorem in [BB], whose proof inspired the current result. If  $\lambda \neq \mu$ , then

$$\alpha^{\lambda^\pm}[\widehat{\mu}^1] = \alpha^{\lambda^\pm}[\widehat{\mu}^2] = \frac{1}{2}\chi^\lambda(\widehat{\mu}) \neq 0.$$

By a similar argument as above applied to  $\lambda^+$  and  $\lambda^-$  in place of  $\lambda$ , we have the following analogue of  $(\star)$ :

$$\begin{aligned} \text{either} \quad & \langle \alpha^{\mu^+} \otimes \alpha^{\mu^+}, \alpha^{\lambda^+} \rangle = \langle \alpha^{\mu^+} \otimes \alpha^{\mu^+}, \alpha^{\lambda^-} \rangle \neq 0, \\ \text{or} \quad & \langle \alpha^{\mu^+} \otimes \alpha^{\mu^-}, \alpha^{\lambda^+} \rangle = \langle \alpha^{\mu^+} \otimes \alpha^{\mu^-}, \alpha^{\lambda^-} \rangle \neq 0. \end{aligned}$$

This implies that  $\alpha^{\lambda^+}$  and  $\alpha^{\lambda^-}$  are components of  $\operatorname{Res}_{A_n}^{S_n}(\chi^\mu \otimes \chi^\mu)$ . Therefore,  $\chi^\lambda$  is a component of  $\chi^\mu \otimes \chi^\mu$ , as desired. This completes the proof of the  $\lambda = \lambda'$  case, and finishes the proof of the lemma.  $\square$

### 3 Proof of Saxl conjecture for “near”-hooks and “near”-two-rows

We apply Lemma 1.3 to prove the partial cases of Saxl conjecture, by computing the characters  $\chi^\lambda[\widehat{\rho}_k]$ . Computing these characters requires some results on partitions into certain part sizes, as stated below.

#### 3.1 Partitions into finite arithmetic progressions

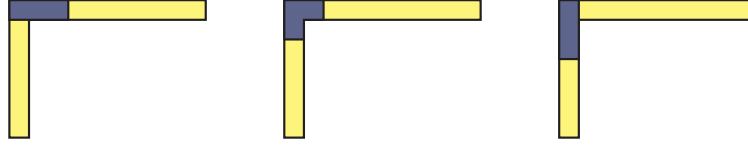
Denote by  $R = R(a, m, k) = \{a, a + m, a + 2m, \dots, a + km\}$  a finite arithmetic progression, with  $a, m \geq 1$ , such that  $\gcd(a, m) = 1$  as above. Denote by  $\pi'_R$  the coefficients in

$$\sum_{n=0}^N \pi'_R(n) t^n = \prod_{r=0}^k (1 + t^{a+rm}),$$

where  $N = (k+1)a + \binom{k+1}{2}m$  is the largest degree with a nonzero coefficient. Note that the sequence  $\{\pi'_R(n)\}$  is symmetric:

$$\pi'_R(n) = \pi'_R(N - n).$$

The following special case of a general result by Odlyzko and Richmond [OR] is the key tool we use throughout the paper.



**Fig. 1:** Three ways to place a rim-hook of length 3 into a hook diagram.

**Theorem 3.1 (JOR)** For every  $a$  and  $m$  with  $\gcd(a, m) = 1$ , there exists a constant  $L = L(a, m)$ , such that for every  $R = R(a, m, k)$  as above,

$$\pi'_R(n+1) > \pi'_R(n) > 0, \quad \text{for all } L \leq n < \lfloor N/2 \rfloor.$$

### 3.2 Proof [sketch] of Theorem 1.4

Let  $n = \binom{k+1}{2}$ , so that  $\rho_k \vdash n$ . Note that  $\widehat{\rho}_k = (2k-1, 2k-5, 2k-9, \dots)$ .

**Lemma 3.2** There exists a constant  $L$ , such that  $g(\rho_k, \rho_k, (n-\ell, 1^\ell)) > 0$ , for all  $L \leq \ell < n/2$ .

When  $\ell < k$  we use a particular simple construction with Blasiak's combinatorial interpretation [Bla] for  $g(\lambda, \mu, \nu)$  when  $\nu$  is a hook, and obtain the full result for hooks:

**Corollary 3.3** For  $k$  large enough, we have  $g(\rho_k, \rho_k, (n-\ell, 1^\ell)) > 0$ , for all  $1 \leq \ell \leq n-1$ .

**Proof of Lemma 3.2:** Let  $\lambda = (n-\ell, 1^\ell)$ . There are two different cases: odd  $k$  and even  $k$ , which correspond to the smallest principal hooks  $(\dots, 9, 5, 1)$  and  $(\dots, 11, 7, 3)$ , respectively.

Let first  $k$  be even, then  $\widehat{\rho}_k = \{2k-1, \dots, 7, 3\}$ . We evaluate the character by the well-known Murnagahn-Nakayama rule (see e.g. [Sta2, §7.17]). There are three ways to fit a 3-rim hook in the hook  $\lambda$ , as Figure 3.2 indicates, so

$$\chi^\lambda[\widehat{\rho}_k] = \pi'_R(\ell) - \pi'_R(\ell-1) + \pi'_R(\ell-2),$$

where  $R = \{2k-1, \dots, 7, 3\}$ . By Theorem 3.1 we have  $\pi'_R(\ell) - \pi'_R(\ell-1) > 0$ , so the character is nonzero.

The odd  $k$  case is even easier: hook 1 can be placed in  $[\lambda]$  in a unique way, after which we get  $\chi^\lambda[\widehat{\rho}_k] = \pi'_R(\ell)$ , which is the number of partitions into distinct parts  $R = \{5, 9, 13, \dots, 2k-1\}$ . This is again nonzero by Theorem 3.1.

In both cases  $\chi^\lambda[\widehat{\rho}_k] > 0$  and the Lemma 1.3 now implies the result.  $\square$

**Lemma 3.4** There exists a constant  $L$ , such that for all  $L < \ell \leq n/2$  we have  $g(\rho_k, \rho_k, (n-\ell, \ell)) > 0$ .

**Proof:**

Recall the Frobenius formula

$$\chi^{(n-\ell, \ell)} = \chi^{(n-\ell) \circ (\ell)} - \chi^{(n-\ell+1) \circ (\ell-1)}.$$

By the Murnagahn-Nakayama rule for skew shapes, we have:

$$\chi^{(n-m) \circ (m)}[\widehat{\rho}_k] = \pi'_R(m),$$



where  $R = \{2k - 1, 2k - 5, \dots\}$ . Therefore, for  $L \leq \ell \leq n/2$ , by Theorem 3.1 we have

$$\chi^{n-\ell, \ell}[\widehat{\eta}_k] = \pi'_R(\ell) - \pi'_R(\ell - 1) > 0.$$

Now Lemma 1.3 implies the result.  $\square$

For small values of  $\ell$  (specifically  $\ell < k$ ) there is a combinatorial interpretation in [BO2], which can be applied in this case, and complete the result to

**Corollary 3.5** *For  $k$  large enough, we have  $g(\rho_k, \rho_k, (n - \ell, \ell)) > 0$ , for all  $0 \leq \ell \leq n/2$ .*

When  $\lambda$  “near-hook” and “near-two-row” shapes the proofs use Gambieli and Frobenius formulas to evaluate the characters  $\chi^\lambda[\widehat{\rho}_k]$  as certain differences of partition functions  $\pi'_R(\ell)$ , similar to the proofs above. Again, Theorem 3.1 can be applied to show that these characters are nonzero. However, in these cases there are no other interpretations that can be used to decide the positivity of  $g(\rho_k, \rho_k, \lambda)$  for  $\lambda < L$ . The full proofs and expressions can be found in [PPV]. Together these imply Theorem 1.4.

## 4 Extensions of Sylvester’s theorem

For every two partitions of size  $n$ , define

$$a_k(\lambda, \mu) = \sum_{\alpha \vdash k, \beta \vdash n-k} c_{\alpha\beta}^\lambda c_{\alpha\beta}^\mu,$$

where  $c_{\pi\theta}^\nu$  are the *Littlewood–Richardson coefficients*.

**Lemma 4.1** *For any two partitions  $\lambda, \mu \vdash n$ , the sequence*

$$a_0(\lambda, \mu), \dots, a_n(\lambda, \mu)$$

*is symmetric and unimodal.*

**Proof:** We use the language of symmetric functions. Recall that the inner product  $*$  in the ring of symmetric functions is defined on the basis of Schur functions as

$$s_\lambda(x) * s_\mu(x) = \sum_{\nu \vdash n} g(\lambda, \mu, \nu) s_\nu(x).$$

We start with *Littlewood’s identity*:

$$(\circ) \quad s_\lambda * (s_\pi s_\theta) = \sum_{\alpha \vdash k, \beta \vdash n-k} c_{\alpha\beta}^\lambda (s_\alpha * s_\pi)(s_\beta * s_\theta),$$

where  $\lambda \vdash n$ ,  $\pi \vdash k$  and  $\theta \vdash n - k$  (see [Lit]).

Since  $s_a$  corresponds to the trivial representation, we have  $s_\nu * s_a = s_\nu$ , for all  $\nu \vdash a$ . For  $\pi = (k)$  and  $\theta = (n - k)$ , we obtain:

$$s_\lambda * (s_k s_{n-k}) = \sum_{\alpha \vdash k, \beta \vdash n-k} c_{\alpha\beta}^\lambda s_\alpha s_\beta = \sum_{\alpha \vdash k, \beta \vdash n-k, \nu \vdash n} c_{\alpha\beta}^\lambda c_{\alpha\beta}^\nu s_\nu.$$

Now let  $\tau = (n - k, k)$ , where  $k \leq n/2$ . By the Jacobi–Trudi formula, we have:

$$s_\tau = s_k s_{n-k} - s_{k-1} s_{n-k+1}.$$

We obtain:

$$s_\lambda * s_\tau = s_\lambda * (s_k s_{n-k}) - s_\lambda * (s_{k-1} s_{n-k+1}) = \sum_{\nu} a_k(\lambda, \nu) s_\nu - a_{k-1}(\lambda, \nu) s_\nu.$$

Therefore, the Kronecker coefficient  $g(\lambda, \mu, \tau)$  is equal to the coefficient at  $s_\mu$  in the expansion of  $s_\lambda * s_\tau$  in terms of Schur functions:

$$g(\lambda, \mu, \tau) = a_k(\lambda, \mu) - a_{k-1}(\lambda, \mu).$$

Since  $g(\lambda, \mu, \tau) \geq 0$ , the unimodality follows. The symmetry is clear from the definition and the symmetry of the LR coefficients.  $\square$

**Proof (sketch) of Theorem 1.5:** Apply Lemma 4.1 with  $\lambda = (m^\ell, 1^r)$  and  $\mu = (m + r, m^{\ell-1})$ . Denote by  $\bar{\beta}$  the skew partition  $(m^\ell)/(m^\ell - \beta)$ , where  $m^\ell - \beta$  is the partition  $(m - \beta_\ell, m - \beta_{\ell-1}, \dots, m - \beta_1)$ . Using combinatorics of Littlewood–Richardson coefficients, we obtain (see [PP-u]) that

$$c_{\alpha\beta}^\lambda c_{\alpha\beta}^\mu = \begin{cases} 1 & \text{if } \bar{\beta} \subset \alpha \text{ and } \alpha/\bar{\beta} \sim 1^{or} \\ 0 & \text{otherwise,} \end{cases}$$

where  $\sim 1^{or}$  means that the skew shape consists of  $r$  disconnected boxes. This implies that

$$a_k(\lambda, \mu) = p_k(\ell, m, r)$$

and the unimodality follows from Lemma 4.1.  $\square$

## 5 Strict unimodality of Gaussian coefficients

The following result lies in the heart of the proof of the theorem. Although stated combinatorially, the only proof we know is algebraic.

**Lemma 5.1 (Additivity Lemma)** *Suppose inequalities  $(\circ)$  as in Theorem 1.6 hold for pairs  $(\ell, m_1)$  and  $(\ell, m_2)$ , with at least one of  $\ell, m_1, m_2$  even and at least one  $\geq 3$ . Then  $(\circ)$  holds for  $(\ell, m_1 + m_2)$ .*

The proof relies on the following results, conjectured by Klyachko in 2004, and recently proved in [CHM] and [Man]:

**Theorem 5.2 (Semigroup property)** *Suppose  $\lambda, \mu, \nu, \alpha, \beta, \gamma$  are partitions of  $n$ , such that  $g(\lambda, \mu, \nu) > 0$  and  $g(\alpha, \beta, \gamma) > 0$ . Then  $g(\lambda + \alpha, \mu + \beta, \nu + \gamma) > 0$ .*

**Proof of Lemma 5.1:** By Lemma 4.1 and the proof of Theorem 1.5 with  $r = 0$  we have that

$$g((m^\ell), (m^\ell), (n - k, k)) = p_k(m, \ell) - p_{k-1}(m, \ell).$$

Let  $\lambda = \mu = (m_1^\ell)$ ,  $\alpha = \beta = (m_2^\ell)$ ,  $\nu = (\ell m_1 - r, r)$ ,  $\gamma = (\ell m_2 - s, s)$ . By the strict unimodality assumption for  $(\ell, m_1)$  and  $(\ell, m_2)$ , we have

$$g(m_1^\ell, m_1^\ell, \nu) > 0, \quad g(m_2^\ell, m_2^\ell, \gamma) > 0,$$

for all  $r, s \geq 0, \neq 1$ . Apply Theorem 5.2 to the fixed partitions above. Now, for all  $k = r + s$ , we then have

$$g((m_1 + m_2)^\ell, (m_1 + m_2)^\ell, \tau_k) = g(m_1^\ell + m_2^\ell, m_1^\ell + m_2^\ell, \nu + \gamma) > 0,$$

where  $n = (m_1 + m_2)\ell$  and  $\tau_k = (n - k, k)$  as before. For  $k \leq 3$  we can choose  $(r, s) = (0, k)$  or  $(k, 0)$ , as at it is implicit that  $\ell, m_1, m_2 \geq 2$  and one of them is  $\geq 3$ . For  $3 < k \leq \lfloor n/2 \rfloor - 1$  we have that  $k \leq \lfloor \ell m_1/2 \rfloor + \lfloor \ell m_2/2 \rfloor$ , so there are values  $r, s \geq 2$ ,  $r \leq \lfloor \ell m_1/2 \rfloor$  and  $s \leq \lfloor \ell m_2/2 \rfloor$ , such that  $k = r + s$ . Finally, when  $k = \lfloor n/2 \rfloor$ , by the parity conditions we have that at least one of  $\ell m_1, \ell m_2$  is even, so we can choose  $(r, s) = (\ell m_1/2, \lfloor \ell m_2/2 \rfloor)$  or  $(\lfloor \ell m_1/2 \rfloor, \ell m_2/2)$ .  $\square$

**Theorem 5.3** *Let  $m, \ell \geq 2$ . Strict unimodality  $(\circ)$  as in Theorem 1.6 holds if and only if  $\ell = m = 2$  or  $\ell, m \geq 5$  with the exception of (assuming  $\ell \leq m$ )*

$$(\ell, m) = (5, 6), (5, 10), (5, 14), (6, 6), (6, 7), (6, 9), (6, 11), (6, 13), (7, 10).$$

**Proof:** A direct calculation gives strict unimodality for each  $\ell \in \{8, \dots, 15\}$ , and  $8 \leq m < 16$ . For each fixed  $\ell \in \{8, \dots, 15\}$  and  $m \geq 16$ , we have that  $m = 8a + b$  for  $a \geq 1$  and  $8 \leq b < 16$ . Applying the additivity lemma successively with  $\ell, m_1 = 8k + b, m_2 = 8$  for  $k = 0, 1, \dots, a - 1$ , shows that  $(\circ)$  holds for all  $\ell \in \{8, \dots, 15\}$  and  $m \geq 16$ .

Fixing any  $m \geq 8$  and applying the additivity lemma in the direction of  $\ell$  the same way by expressing  $\ell = 8a' + b'$ , shows that  $(\circ)$  holds for all  $m, \ell \geq 8$ .

A direct calculation also gives strict unimodality for all values of  $\ell \in \{5, 6, 7\}$  and  $5 \leq m \leq 20$  with the exception of the listed cases, where the middle three coefficients of the expansion of  $\binom{\ell+m}{m}_q$  are equal. Now we apply the additivity lemma for each value of  $\ell = 5, 6, 7$  and  $m = 10a + b$  where  $10 \leq b \leq 19$  and induct over  $a$  with the values  $m_1 = 10(a - 1) + b$  and  $m_2 = 10$ . The cases  $\ell > m$  follow from the symmetry.

Now, case  $\ell = 2$  is straightforward, since  $p_{2i}(2, m) = p_{2i+1}(2, m)$  for all  $i < n/4$ . On the other hand, cases  $\ell = 3, 4$  have been studied in [Lin, W] using an explicit symmetric chain decomposition. Since all chain lengths there are  $\geq 3$ , we obtain equalities for the middle coefficients.  $\square$

## Acknowledgements

We are very grateful to Jan Saxl for telling us about his conjecture, and to Jonah Blasiak, Matt Boylan, Francesco Brenti, Bob Guralnick, Stephen DeSalvo, Christian Ikenmeyer, Hari Narayanan, Rosa Orellana, Sinai Robins, Raphaël Rouquier, Richard Stanley, Pham Huu Tiep, Gjergji Zaimi and Fabrizio Zanello for helpful remarks and useful references. We would like to thank Andrew Soffer for helpful computer computations. We would like to credit to `MathOverflow` for providing a forum where such questions can be asked.<sup>(vi)</sup>

<sup>(vi)</sup> Specifically, the references in the answers to this `MathOverflow` question proved very useful: <http://mathoverflow.net/questions/111507/>

## References

- [BO2] C. M. Ballantine and R. C. Orellana, A combinatorial interpretation for the coefficients in the Kronecker product  $s_{(n-p,p)} * s_\lambda$ , *Sém. Lothar. Combin.* **54A** (2006), Art. B54Af, 29 pp.
- [BB] C. Bessenrodt and C. Behns, On the Durfee size of Kronecker products of characters of the symmetric group and its double covers, *J. Algebra* **280** (2004), 132–144.
- [Bla] J. Blasiak, Kronecker coefficients for one hook shape, [arXiv:1209.2018](https://arxiv.org/abs/1209.2018) (2012).
- [BOR] E. Briand, R. Orellana and M. Rosas, Reduced Kronecker coefficients and counter-examples to Mulmuley’s strong saturation conjecture SH, *Comput. Complexity* **18** (2009), 577–600.
- [B1] F. Brenti, Unimodal, log-concave, and Pólya frequency sequences in combinatorics, *Mem. AMS*, No. 413, 1989, 106 pp.
- [B2] F. Brenti, Log-concave and unimodal sequences in algebra, combinatorics, and geometry: an update, in *Contemp. Math.* **178**, AMS, Providence, RI, 1994, 71–89.
- [Bür] P. Bürgisser, Review of [MS], [MR2421083](https://arxiv.org/abs/2009j:68067) (2009j:68067).
- [BWZ] A. A. H. Brown, S. van Willigenburg and M. Zabrocki, Expressions for Catalan Kronecker products, *Pacific J. Math.* **248** (2010), 31–48.
- [CHM] M. Christandl, A. W. Harrow, G. Mitchison, Nonzero Kronecker coefficients and what they tell us about spectra, *Comm. Math. Phys.* **270** (2007), 575–585.
- [Dh] V. Dhand, A combinatorial proof of strict unimodality for q-binomial coefficients, preprint, [arXiv:1402.1199](https://arxiv.org/abs/1402.1199), 2014.
- [Dvir] Y. Dvir, On the Kronecker product of  $S_n$  characters, *J. Algebra* **154** (1993), 125–140.
- [HSTZ] G. Heide, J. Saxl, P. H. Tiep and A. E. Zalesski, Conjugacy action, induced representations and the Steinberg square for simple groups of Lie type, *Proc. Lond. Math. Soc.* **106** (2013), 908–930.
- [HZ] G. Heide and A. E. Zalesski, Passman’s problem on adjoint representations, in *Contemp. Math.* **420**, AMS, Providence, RI, 2006, 163–176.
- [Ike] C. Ikenmeyer, *Geometric Complexity Theory, Tensor Rank, and Littlewood-Richardson Coefficients*, thesis, University of Paderborn, 2012; available at <http://bit.ly/SVIR0M>
- [JK] G. D. James and A. Kerber, *The Representation Theory of the Symmetric Group*, Cambridge U. Press, Cambridge, 2009.
- [Lin] B. Lindström, A partition of  $L(3, n)$  into saturated symmetric chains, *Eur. J. Combin.* **1** (1980), 61–63.
- [Lit] D. E. Littlewood, The Kronecker product of symmetric group representations, *J. London Math. Soc.* **31** (1956), 89–93.
- [Mac] I. G. Macdonald, *Symmetric functions and Hall polynomials* (Second ed.), Oxford U. Press, New York, 1995.
- [Man] L. Manivel, On rectangular Kronecker coefficients, *J. Algebraic Combin.* **33** (2011), 153–162.
- [Mul] K. D. Mulmuley, Geometric complexity theory VI: The flip via positivity, [arXiv:0704.0229](https://arxiv.org/abs/0704.0229)
- [MNS] K. D. Mulmuley, H. Narayanan and M. Sohoni, Geometric complexity theory III. On deciding nonvanishing of a Littlewood-Richardson coefficient, *J. Algebraic Combin.* **36** (2012), 103–110.
- [MS] K. D. Mulmuley and M. Sohoni, Geometric complexity theory II. Towards explicit obstructions for embeddings among class varieties, *SIAM J. Comput.* **38** (2008), 1175–1206.
- [Nar] H. Narayanan, On the complexity of computing Kostka numbers and Littlewood-Richardson coefficients, *J. Algebraic Combin.* **24** (2006), 347–354.
- [O’H] K. M. O’Hara, Unimodality of Gaussian coefficients: a constructive proof, *J. Combin. Theory, Ser. A* **53** (1990), 29–52.
- [OR] A. M. Odlyzko and L. B. Richmond, On the unimodality of some partition polynomials, *European J. Combin.* **3** (1982), 69–84.
- [Pak] I. Pak, Partition Bijections, a Survey, *Ramanujan J.* **12** (2006), 5–75.
- [PP] I. Pak and G. Panova, Combinatorics and complexity of Kronecker coefficients, in preparation.

- [PP-u] I. Pak and G. Panova, Unimodality via Kronecker products, *J. Alg. Combinatorics* (2014), to appear, [arXiv:1304.5044](https://arxiv.org/abs/1304.5044).
- [PP-s] I. Pak and G. Panova, Strict unimodality of  $q$ -binomial coefficients, *C. R. Acad. Sci. Paris, Ser. I* (2013)
- [PPV] I. Pak, G. Panova and E. Vallejo, Kronecker products, characters, partitions, and the tensor square conjectures, submitted (2013), [arXiv:1304.0738](https://arxiv.org/abs/1304.0738)
- [Pro] R. A. Proctor, Solution of two difficult combinatorial problems with linear algebra, *Amer. Math. Monthly* **89** (1982), 721–734.
- [Reg] A. Regev, Kronecker multiplicities in the  $(k, l)$  hook are polynomially bounded, [arXiv:1011.1636](https://arxiv.org/abs/1011.1636).
- [Rem] J. B. Remmel, A Formula for the Kronecker Products of Schur Functions of Hook Shapes, *J. of Algebra* **120** (1989), 100–118.
- [RW] J. B. Remmel and T. Whitehead, On the Kronecker product of Schur functions of two row shapes, *Bull. Belg. Math. Soc. Simon Stevin* **1** (1994), 649–683.
- [Sag] B. E. Sagan, *The symmetric group* (Second ed.), Springer, New York, 2001.
- [Saxl] J. Saxl, The complex characters of the symmetric groups that remain irreducible in subgroups, *J. Algebra* **111**, (1987), 210–219.
- [Sta1] R. P. Stanley, Log-concave and unimodal sequences in algebra, combinatorics, and geometry, in *Ann. New York Acad. Sci.* **576**, New York Acad. Sci., New York, 1989, 500–535.
- [Sta2] R. P. Stanley, *Enumerative combinatorics*, Vol. 2, Cambridge U. Press, Cambridge, 1999.
- [S1] R. P. Stanley, Unimodal sequences arising from Lie algebras, in *Lecture Notes in Pure and Appl. Math.* **57**, Dekker, New York, 1980, 127–136.
- [S2] R. P. Stanley, Weyl groups, the hard Lefschetz theorem, and the Sperner property, *SIAM J. Algebraic Discrete Methods* **1** (1980), 168–184.
- [SZ] D. Stanton and D. Zeilberger, The Odlyzko conjecture and O’Hara’s unimodality proof, *Proc. AMS* **107** (1989), 39–42.
- [Syl] J. J. Sylvester, Proof of the hitherto undemonstrated Fundamental Theorem of Invariants, *Philosophical Magazine* **5** (1878), 178–188; reprinted in *Coll. Math. Papers*, vol. 3, Chelsea, New York, 1973, 117–126; available at <http://tinyurl.com/c94pphj>
- [Val1] E. Vallejo, Stability of Kronecker products of irreducible characters of the symmetric group, *El. J. Combin.* **6** (1999), RP 39, 7 pp.
- [Val2] E. Vallejo, Multiple hooks in Kronecker products of  $S_n$  characters and a conjecture of Berele and Imbo, *J. Algebra* **259** (2003), 300–309.
- [Val3] E. Vallejo, A diagrammatic approach to Kronecker squares, preprint (2013), [arXiv:1310.8362](https://arxiv.org/abs/1310.8362).
- [Wen] X. Wen, Computer-generated symmetric chain decompositions for  $L(4, n)$  and  $L(3, n)$ , *Adv. Appl. Math.* **33** (2004), 409–412.
- [W] D. B. West, A symmetric chain decomposition of  $L(4, n)$ , *Eur. J. Combin.* **1** (1980), 379–383.
- [Zan] F. Zanello, Zeilberger’s KOH theorem and the strict unimodality of  $q$ -binomial coefficients, preprint (2013), [arXiv:1311.4480](https://arxiv.org/abs/1311.4480).
- [Zei] D. Zeilberger, Kathy O’Hara’s constructive proof of the unimodality of the Gaussian polynomials, *Amer. Math. Monthly* **96** (1989), 590–602.