SCHUBERT CALCULUS AND TORSION

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Abstract. We observe that certain numbers occurring in Schubert calculus for $SL_n$ also occur as entries in intersection forms controlling decompositions of Soergel bimodules and parity sheaves in higher rank. These numbers grow exponentially in the rank. This observation gives many counter-examples to Lusztig’s conjecture on the characters of simple rational modules for $SL_n$ over a field of positive characteristic. We explain why our examples also give counter-examples to the James conjecture on decomposition numbers for symmetric groups.

Dedicated to Meg and Gong.

1. Introduction

Let $G$ be a connected algebraic group over an algebraically closed field. A basic question in representation theory asks for the dimensions and characters of the simple rational $G$-modules. Structure theory of algebraic groups allows one to assume that $G$ is reductive. If the ground field is of characteristic zero, then the theory runs parallel to the well-understood theory for compact Lie groups. In positive characteristic $p$, Steinberg’s tensor product theorem, the linkage principle and Jantzen’s translation principle reduce this to a question about finitely many modules which occur in the same block as the trivial module (the “principal block”). For these modules Lusztig has proposed a conjecture if $p \geq h$, where $h$ denotes the Coxeter number of the root system of $G$ [Lus80]. He conjectures an expression for the characters of the simple modules in terms of affine Kazhdan-Lusztig polynomials and the (known) characters of standard modules.

Lusztig’s conjecture has been shown to hold for $p$ large (without an explicit bound) thanks to work of Andersen, Jantzen and Soergel [AJS94], Kashiwara and Tanisaki [KT93, KT94], Kazhdan and Lusztig [KL93, KL94a, KL94b] and Lusztig [Lus94]. Alternative proofs for large $p$ have been given by Arkhipov, Bezrukvanikov and Ginzburg [BG04], Bezrukvanikov, Mirkovic and Rumynin [BMR08] and Fiebig [Fie11]. Fiebig also gives an explicit (enormous) bound [Fie12], which is exponential in the rank, and establishes the multiplicity one case [Fie10]. For any fixed $G$ and “reasonable” $p$ very little is known: the case of rank 2 groups can be deduced from Jantzen’s sum formula, and intensive computational efforts have checked the conjecture for small $p$ and certain groups, all of rank $\leq 5$. There is no conjecture as to what happens if $p$ is smaller than the Coxeter number.

In [Soe00] Soergel introduced a subquotient of the category of rational representations, dubbed the “subquotient around the Steinberg weight”, as a toy model for

\footnote{Lusztig first proposed his conjecture under the restriction $p \geq 2h - 3$. This is not the original formulation, see [Jant03, §4] and [Jant03, §8.22] for a discussion. The statement of the conjecture for $p \geq h$ seems to have first been made by Kato [Kat85], who also showed that Lusztig’s conjecture is compatible with Steinberg’s tensor product theorem.}
the study of Lusztig’s conjecture. Whilst the full version of Lusztig’s conjecture is based on the combinatorics of alcoves and the affine Weyl group, the subquotient around the Steinberg weight is controlled by the finite Weyl group, and behaves like a modular version of category $O$. Lusztig’s conjecture implies that the multiplicities in the subquotient around the Steinberg weight are given by finite Kazhdan-Lusztig polynomials. Thus Lusztig’s conjecture implies that “the subquotient around the Steinberg weight satisfies the Kazhdan-Lusztig conjecture”.

In [Soe00] Soergel also explains how the subquotient around the Steinberg weight is controlled by Soergel bimodules. This allows him to relate this category to the category of constructible sheaves on the Langlands dual flag variety, with coefficients in the field of definition of $G$. Using Soergel’s results and the theory of parity sheaves [JMW09], one can see that a part of Lusztig’s conjecture for $p > h$ is equivalent to absence of $p$ torsion in the stalks and costalks of integral intersection cohomology complexes of Schubert varieties in the flag variety. It has been known since the birth of the theory of intersection cohomology that $2$-torsion occurs in type $B_2$, and $2$ and $3$ torsion occurs in type $G_2$. For over a decade no other examples of torsion were known. In 2002 Braden discovered 2-torsion in the stalks of integral intersection cohomology complexes on flag varieties of types $D_4$ and $A_7$. Much more recently Polo discovered 3-torsion in the cohomology of the flag variety of type $E_6$ and $n$-torsion in a flag variety of type $A_{4n-1}$. Polo’s (as yet unpublished) results are significant, as they emphasise how little we understand in high rank (see the final lines of [Wil12]).

In general these topological calculations appear extremely difficult (for a sample computation see Braden’s appendix to [WB12]). Recently Ben Elias and the author have found a presentation for the monoidal category of Soergel bimodules by generators and relations, completing work initiated by Libedinsky [Lib10] and Elias-Khovanov [EK10]. One of the applications of this theory is that one can decide whether a given intersection cohomology complex has $p$-torsion in its stalks or costalks (the bridge between intersection cohomology and Soergel bimodules is provided by the theory of parity sheaves). The basic idea is as follows: given any pair $(w, x)$, where $x, w \in W$ and $w$ is a reduced expression for $w \in W$, one has an “intersection form”, an integral matrix. Then the stalks of the intersection cohomology complex $w$ are free of $p$-torsion if no elementary divisors of the intersection forms associated to all elements $x \leq w$ are divisible by $p$. In principle, this gives an algorithm to decide whether Lusztig’s conjecture is correct around the Steinberg weight. This algorithm (in a slightly different form) was discovered independently by Libedinsky [Lib].

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2One can also perform this calculation using the theory of moment graphs [FW]. However the computations using generators and relations are generally much simpler.

3The terminology “intersection form” comes from geometry: in de Cataldo and Migliorini’s Hodge theoretic proof of the decomposition theorem, a key role is played by certain intersection forms associated to the fibres of proper maps [dCM02, dCM05]. In our setting, these intersection forms are associated to the fibres of Bott-Samelson resolutions of Schubert varieties. The relevance of these forms for the study of torsion in intersection cohomology was pointed out in [JMW09].

4One can extend this to the full version of Lusztig’s conjecture by using a certain subset of the affine Weyl group, thanks to the work of Fiebig [Fie11]. Although it seems likely that the converse holds, at present one only knows one implication: the absence of $p > h$ torsion implies the truth of Lusztig’s conjecture in characteristic $p$. 
The generators and relations approach certainly makes calculations easier. However, this approach still has its difficulties: the diagrammatic calculations remain extremely subtle, and the “light leaves” basis in which the intersection form is calculated depends on additional choices which seem difficult to make canonical. Recent progress in this direction has been made by Xuhua He and the author, who discovered that certain entries in the intersection form (which in some important examples are all entries) are canonical and may be evaluated in terms of expressions in the nil Hecke ring.

The main result of this paper may be seen as an example of this phenomenon. We observe that one may embed certain structure constants of Schubert calculus for \( SL_n \) as the entries of \( 1 \times 1 \) intersection forms associated to pairs \((w, x)\) in higher rank groups. In this way one can produce many new examples of torsion which grow exponentially in the rank. For example, using Schubert calculus for the flag variety of \( SL_4 \) we observe that the Fibonacci numbers \( F_n \) and \( F_{n+1} \) occur as torsion in \( SL_{4n+7} \). We deduce that there is no linear function \( f(h) \) of \( h \) such that Lusztig’s conjecture holds for all \( p \geq f(h) \). It seems likely that the prime factors occurring grow exponentially\(^5\) which would imply the non-existence of any polynomial bound.

Finally, there is a related conjecture due to James \([\text{Jam90}]\) concerning the simple representations of the symmetric group in characteristic \( p \). When combined with known results about the decomposition numbers for Hecke algebras at roots of unity, the James conjecture would yield the decomposition numbers for symmetric groups \( S_n \) in characteristic \( p > \sqrt{n} \). In the final section of the paper we explain why our counter-examples to Lusztig’s conjecture for \( SL_N \) with \( p > \binom{N}{2} \) imply that the James conjecture is incorrect for \( S_p(\binom{N}{2}) \).

1.1. Main result. Let \( R = \mathbb{Z}[x_1, x_2, \ldots, x_n] \) be a polynomial ring in \( n \) variables graded such that \( \deg x_i = 2 \) and let \( W = S_n \) the symmetric group on \( n \)-letters. Then \( S_n \) acts by permutation of variables on \( R \). Let \( s_1, \ldots, s_{n-1} \) denote the simple transpositions of \( S_n \) and let \( \ell \) denote the corresponding length function. Let \( \partial_i \) denote the \( i^{th} \) divided difference operator:

\[
\partial_i(f) = \frac{f - s_i f}{x_i - x_{i+1}} \in R.
\]

For any element \( w \in S_n \) we set \( \partial_w = \partial_{i_1} \cdots \partial_{i_m} \) where \( w = s_{i_1} \cdots s_{i_m} \) is a reduced expression for \( w \).

Consider elements of the form

\[
C = \partial_{w_m}(x_1^{a_m}x_n^{b_m} \partial_{w_{m-1}}(x_1^{a_{m-1}}x_n^{b_{m-1}} \cdots \partial_{w_1}(x_1^{a_1}x_n^{b_1}) \cdots))
\]

where \( w_i \in S_n \) are arbitrary. We assume that \( \sum \ell(w_i) = a + b \) where \( a = \sum a_i \) and \( b = \sum b_i \) so that \( C \in \mathbb{Z} \) for degree reasons. Given a subset \( I \subset \{1, \ldots, n-1\} \) let \( w_I \) denote the longest element in the parabolic subgroup \( \langle s_j \rangle_{j \in I} \). Our main theorem is the following:

**Theorem 1.1.** Suppose that \( C \neq 0 \). Then there exists a (reduced) expression \( w \) for an element of \( S_{a+n+b} \) such that the intersection form of \( w \) at \( w_I \), where \( I = \{1, 2, \ldots, a + n + b - 1\} \setminus \{a, a+n\} \), is the matrix \((\pm C)\).

\(^5\)I expect to be able to prove this in the near future. This statement would already be a theorem if one knew that infinitely many Fibonacci numbers are prime, which number theorists seem to expect.
The construction of the expression $w$ is explicit and combinatorial based on $w_1, \ldots, w_m, a_1, \ldots, a_m$ and $b_1, \ldots, b_m$. In §6 we will see that the numbers $C$ (and probably their prime factors) grow exponentially in $h = n + a + b$.

1.2. Schubert calculus. Let us briefly explain why “Schubert calculus” occurs in the title. In some sense this explains the meaning of the above constants $C$.

Consider the coinvariant ring $H$ for the action of $W = S_n$ on $R$. That is, $H$ is equal to $R$ modulo the ideal generated by $W$-invariant polynomials of positive degree. The Borel isomorphism gives a canonical identification of $H$ with the integral cohomology of the complex flag variety of $G = SL_n$.

The divided difference operators $\partial_w$ act on $H$, as do elements of $R$. The coinvariant ring $H$ has a graded $\mathbb{Z}$-basis given by the Schubert classes $\{X_w | w \in S_n\}$ (normalised with $X_{\text{id}} = x_n^{n-1} x_{n-2}^{n-2} \cdots x_1^{n-1}$ and $X_w = \partial_w X_{\text{id}}$). We have:

\begin{equation}
\partial_i X_w = \begin{cases} X_{s_i w} & \text{if } s_i w < w, \\ 0 & \text{otherwise.} \end{cases}
\end{equation}

The action of multiplication by $f \in R$ of degree two is given as follows (the Chevalley formula):

\begin{equation}
f \cdot X_w = \sum_{t \in T, \ell(tw) = \ell(w)+1} (f, \alpha_i^{\vee}) X_{tw}.
\end{equation}

(Here $T$ denotes the set of reflections (transpositions) in $S_n$, $\ell$ denotes the length function and if $t = (i, j)$ with $i < j$ then $\alpha_i^{\vee} = \varepsilon_i - \varepsilon_j$ where $\{\varepsilon_i\}$ is the dual basis to $x_1, \ldots, x_n$.)

Now consider the numbers one may obtain as coefficients in the basis of Schubert classes by multiplication by $x_1$ and $x_n$ and by applying Demazure operators, starting with $X_{\text{id}}$. Then Theorem 1.1 says that any such number occurs as torsion in $SL_n + a + b$ where $a$ (resp. $b$) counts the number of times that one has applied the operator of multiplication by $x_1$ (resp. $x_n$).

1.3. Note to the reader. This paper is not yet in its final form and should be considered as an announcement, together with a sketch of the argument. It should be possible to replace the diagrammatic proof of the main theorem with a geometric argument, using techniques explained to me by Patrick Polo. I hope to provide both arguments in the final version.

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2. SOERGEL BIMODULES

In this section and the next we give a brief overview of Soergel bimodules and intersection forms. This paper is not self-contained. The main references are [Soe90, Soe92, JM09, EK10, EWb]. The purpose of these two sections is to orient the reader in the literature and give some examples of intersection forms.

Let \((X, R, X^\vee, R^\vee)\) denote a reduced root datum, \(W\) its Weyl group, \(S\subset W\) a fixed choice of simple reflections and \(\{\alpha_s\}_{s\in S}, \{\alpha^\vee_s\}_{s\in S}\) the corresponding simple roots and coroots. We denote by \(\ell : W \to \mathbb{N}\) the length function and \(\leq\) the Bruhat order.

Fix a field \(k\) of coefficients and let \(R = S \otimes_{\mathbb{Z}} k\) denote the symmetric algebra on the \(k\)-vector space \(X \otimes_{\mathbb{Z}} k\), graded so that \(X \otimes_{\mathbb{Z}} k\) is homogenous of degree 2. Then \(R\) is a graded \(W\)-algebra, and given \(s \in S\) we denote by \(R^s\) the invariant subring.

The category of Soergel bimodules \(\mathcal{B}\) is the full additive monoidal graded Karoubian subcategory of graded \(R\)-bimodules generated by \(B_s = R \otimes_{R^s} R(1)\) for all \(s \in S\). (Here \(R \otimes_{R^s} R(1)\) denotes the \(R\)-bimodule \(R \otimes_{R^s} R\) shifted so that \(1 \otimes 1\) is in degree \(-1\).) In other words, the indecomposable Soergel bimodules are the shifts of the indecomposable direct summands of the Bott-Samelson bimodules \(BS(w) = B_{s_1} \otimes_{R} B_{s_2} \otimes_{R} \cdots \otimes_{R} B_{s_m}\) for all words \(w = s_1 s_2 \cdots s_m\) in \(S\). In [Soe07] Soergel proves that the category of Soergel bimodules categorifies the Hecke algebra, as long the characteristic of \(k\) is not 2 and the representation of \(W\) on \(X^\vee \otimes_{\mathbb{Z}} k\) satisfies a non-degeneracy condition (it should be “reflection faithful” [Soe07, Def. 1.5]). The most difficult part of Soergel’s proof is a classification of the indecomposable Soergel bimodules: for all \(w \in W\) there exists an indecomposable Soergel bimodule \(B_w\) which occurs with multiplicity one as a summand of \(BS(w)\) for any reduced expression \(w\) for \(w\), and the set \(\{B_w\}\) coincides with the set of all indecomposable Soergel bimodules, up to shifts in the grading.

**Remark 2.1.** Under mild and explicit restrictions on the characteristic of \(k\), \(B_w\) may be realised as the equivariant intersection cohomology of the indecomposable parity sheaf [JM09] of the Schubert variety labelled by \(w\) in the flag variety of the complex group with root data \((X, R, X^\vee, R^\vee)\) [Fie08, FW]. In particular, if \(k\) is of characteristic zero, then \(B_w\) is the equivariant intersection cohomology of a Schubert variety.

In [EWb] the category of Soergel bimodules is presented by generators and relations, following earlier work of Libedinsky [Lib10] and Elias-Khovanov [EK10]. More precisely, we define a graded \(R\)-linear monoidal category \(\mathcal{D}\) by generators and relations and prove that it is equivalent to the category of Soergel bimodules as an additive graded monoidal category (under the same assumptions on \(k\) and \(X^\vee \otimes_{\mathbb{Z}} k\) as above). We will not repeat the rather complicated list of generators and relations here, see [EWb, §1.4].

**Remark 2.2.** The theory of Soergel bimodules seems to break down if \(k\) is of characteristic 2 or if the representation of \(W\) on \(X^\vee \otimes_{\mathbb{Z}} k\) is not reflection faithful. On
the other hand, the category defined by generators and relations still makes sense and appears to be the correct substitute \[\text{[EWb] §3.2}].

An important tool in the study of Soergel bimodules is Soergel’s hom formula \[\text{[Soe07] Theorem 5.15}\] which describes the graded rank of homomorphisms between Soergel bimodules in terms of the canonical form on the Hecke algebra. This formula was categorified by Libedinsky \[\text{[Lib08]}\] who introduced a recursively defined set of morphisms between Bott-Samelson bimodules, which he called light leaves. Certain compositions of these morphisms, called double leaves, give an \(R\)-basis for morphisms of all degrees between Bott-Samelson bimodules. Light leaves and double leaves morphisms admit a nice diagrammatic description \[\text{[EWb] §1.5 and §6}\].

3. Intersection forms

From now on \(D\) denotes the diagrammatic category of Soergel bimodules as defined in \[\text{[EWb]}\] over the field \(k\). Given any ideal \(I \subseteq W\) (i.e. \(x \leq y \in I \Rightarrow x \in I\)) we denote by \(D_I\) the ideal of \(D\) generated by all morphisms which factor through a Bott-Samelson bimodule \(BS(y)\), where \(y\) is a reduced expression for \(y \in I\).

Given \(x \in W\) we denote by \(D \geq x\) the quotient category \(D/D_x\). We write \(\text{Hom}_{\geq x}\) for (degree zero) morphisms in \(D \geq x\). All Bott-Samelson bimodules \(BS(x)\) corresponding to reduced expressions \(x\) for \(x\) become canonically isomorphic to \(B_x\) in \(D \geq x\). We denote the resulting object simply by \(x\). We have \(\text{End}_{\geq x}(x) = k\).

Given any expression \(w\) in \(S\) the intersection form is the canonical pairing
\[
I_{x,w,d}: \text{Hom}_{\geq x}(x(d), BS(w)) \times \text{Hom}_{\geq x}(BS(w), x(d)) \to \text{End}_{\geq x}(x(d)) = k.
\]

**Lemma 3.1.** The multiplicity of \(B_x(d)\) as a summand of \(BS(w)\) is equal to the rank of \(I_{x,w,d}\).

**Proof.** Because \(B_x\) is indecomposable, \(\text{End}(B_x)\) is a local ring and the radical of \(\text{End}(B_x)\) is the kernel of the canonical surjection
\[
\text{can}: \text{End}(B_x) \to \text{End}_{\geq x}(B_x) = \text{End}_{\geq x}(x) = k.
\]
Now, it is a standard fact (see e.g. \[\text{[JMW05] Lemma 3.1}\]) that the multiplicity of \(B_x(d)\) as a summand of \(BS(w)\) is equal to the rank of the form
\[
\text{Hom}(B_x(d), BS(w)) \times \text{Hom}(BS(w), B_x(d)) \to \text{End}(B_x) \xrightarrow{\text{can}} k.
\]
However, the subspace of \(\text{Hom}(B_x(d), BS(w))\) belonging to \(D \geq x\) is certainly in the kernel of this form \((D \geq x)\) is an ideal), and similarly for \(\text{Hom}(BS(w), B_x(d))\). The form induced on the quotient is precisely the intersection form \(I_{x,w,d}\). \(\square\)

We now want to explain why the forms \(I_{x,w,d}\) are explicit, computable and defined over \(Z\). Given a word \(w = s_1s_2 \ldots s_m\) in \(S\) a subexpression \(e\) of \(w\) is a sequence \(e = e_1 e_2 \ldots e_m\) of 0’s and 1’s. We set \(w^e = s_1^{e_1} \ldots s_m^{e_m}\) and say that the subexpression \(e\) of \(w\) expresses \(w^e\). Given a subexpression \(e\) its Bruhat stroll is the sequence
\[
x_0 = \text{id}, \quad x_1 = s_m^{e_m}, \quad x_2 = s_{m-1}^{e_{m-1}} e_m^{e_m}, \quad \ldots, \quad x_m = w^e.
\]
We decorate each entry in the subsequence with a token U or D (for “up” and “down”) as follows: for \(1 \leq i \leq m, e_i\) is decorated with U if \(s_i x_{m-i} > x_{m-i}\) and is decorated with D if \(s_i x_{m-i} < x_{m-i}\). The defect of the subsequence \(e\) is defined to be the number of occurrences of U0 minus the number of occurrences of D0.
Example 3.2. If $w = sts$ with $s \neq t$ then there are two subexpressions expressing the identity: 000 and 101. They are decorated $U_0 U_0 U_0$, and $D_1 U_0 U_1$ and have defects 3 and 1.

Remark 3.3. See [EWb, §2.4] for a discussion and more examples. The reader should be warned that in this paper we work from right to left (essentially due to the convention that divided difference operators act on the left), rather than from left to right as is done in [EWb].

By Libedinsky’s theorem [EWb, Theorem 1.1] the spaces $\text{Hom}_{\geq x}(x, BS(w))$ and $\text{Hom}_{\geq x}(BS(w), x)$ are free $R$-modules with graded basis given by light leaves corresponding to subexpressions $e$ of $w$ such that $w^e = x$. The degree is given by the defect. Moreover the light leaves morphisms are defined over $\mathbb{Z}$. Hence by using the generators and relations one obtains integral matrices $I_{x,w,d}$ whose reduction modulo $p$ controls the behaviour of the category of Soergel bimodules, as made precise by Lemma 3.1.

Example 3.4. We give two examples of intersection forms (the reader is referred to [EWb] for more details):

1. Assume that $W$ is a dihedral group with simple reflections $s$ and $t$. Let $w = sts$, $x = s$ and $d = 0$. There is only one subexpression of defect 0:
   
   $e = D_0 U_0 U_1$. The corresponding light leaves morphism is

   \[ \begin{array}{c}
   \downarrow \\
   \alpha_t \end{array} \]

   Pairing it with itself we obtain:

   \[ \alpha_t = \partial_s(\alpha_t) + s(\alpha_t) = \partial_s(\alpha_t) \]

   Hence in this case the intersection form is the 1 × 1-matrix:

   \[ (\partial_s(\alpha_t)) = (\langle \alpha_t, \alpha_s^\vee \rangle). \]

   This example show the existence of torsion in the intersection cohomology of the Schubert variety indexed by $sts$ if $\langle \alpha_t, \alpha_s^\vee \rangle < -1$ (as happens in $B_2$ and $G_2$).

2. Assume that $W$ is of type $D_4$ with generators $s, t, u, v$ such that $s, u$ and $v$ commute. Let $w = suvtsuv$, $x = suv$ and $d = 0$. Then there are three subexpressions of defect zero. These subexpressions, and the corresponding light leaves maps are the following:
We leave it to the reader to pair these morphisms and obtain the intersection form
\[
\begin{pmatrix}
0 & -1 & -1 \\
-1 & 0 & -1 \\
-1 & -1 & 0
\end{pmatrix}
\]
Note that the determinant of this matrix is -2. This example of 2-torsion in the $D_4$ flag variety was discovered by Braden [WB12, A.18].

Let $\mathcal{H}$ denote the Hecke algebra of $(W, S)$ normalised as in [Soe97] and let $\{H_x\}$ denote its standard and Kazhdan-Lusztig basis. We denote by $ch : \mathcal{D} \sim \rightarrow \mathcal{H}$ the isomorphism between the split Grothendieck group of Soergel bimodules and the Hecke algebra (see [Soe07, §5] or [EWb, §6.5]).

Let $p$ be the characteristic of $k$ and define
\[pH_x := ch(B_x)\]
then $\{pH_x\}$ is a basis of $H$, the $p$-canonical basis. (It is easily seen to depend only on the characteristic $p$ of $k$, which explains its name. See [Wil12] for a list of its basic properties. For example $H_x = 0H_x = pH_x$ for $p \gg 0$.) Let us write
\[(3.1) \quad H_x = \sum h_{y,x} H_y, \quad pH_x = \sum pH_{y,x} H_y, \quad pH_x = \sum p a_{y,x} H_y.\]

In the following Proposition $I_{x,w,d}$ denotes the integral form of the intersection form defined above.

**Proposition 3.5.** The following are equivalent:

1. The indecomposable Soergel bimodules categorify the Kazhdan-Lusztig basis. That is, $pH_x = H_x$ for all $x \in W$.
2. For all (reduced) expressions $w$ in $S$, all $x \in W$ and all $m \in \mathbb{Z}$ the graded ranks of $I_{x,w,m} \otimes_{\mathbb{Z}} \mathbb{Q}$ and of $I_{x,w,m} \otimes_{\mathbb{Z}} k$ agree.

**Proof.** Soergel’s theorem [Soe01, Lemma 5] implies that the indecomposable Soergel bimodules categorify the Kazhdan-Lusztig basis if $k$ is of characteristic zero (see [EWa] for an algebraic proof of this fact). Now Lemma 3.1 says that (2) holds if and only if $BS(w)$ decomposes the same way over $\mathbb{Q}$ as it does over $k$. Hence (1) and (2) are equivalent.

**Remark 3.6.** The intersection form and the above proposition is one of the tools used by Fiebig to establish his bound [Fie12].

**Remark 3.7.** In fact (1) and (2) are equivalent to $I_{x,w,0} \otimes_{\mathbb{Z}} \mathbb{Q}$ and of $I_{x,w,0} \otimes_{\mathbb{Z}} k$ having the same rank for all reduced expressions $w$ and $x \in W$. (That is we only need to check that the forms for degree zero summands have the correct ranks. This fact plays a key role in [EWa].) We will not need this below.

**Proposition 3.8.** If $p = \text{char } k > h$, the Coxeter number of $W$, and the underlying root system $(X, R, X^\vee, R^\vee)$ is that of a simply connected semi-simple algebraic group, then Lusztig’s conjecture implies that both statements of Proposition 3.5 hold.

**Sketch of proof:** If $p > h$ then $D$ is equivalent to the category of Soergel bimodules $B$. By abuse of notation we also denote by $B_x$ the indecomposable Soergel bimodule parametrized by $x \in W$. We claim that $D_x = B_x \otimes_R k$ is indecomposable as a left
C = R/(R \cdot W) - module. The fact that Lusztig’s conjecture implies (1) follows (with some effort) from [Soe00].

It remains to see that D = is indecomposable. Because the quotient of a local ring if local, it is enough to show that the natural morphism

\[ \phi : \text{Hom}_{R \cdot -}(BS(x), BS(y)) \otimes_R k \rightarrow \text{Hom}_C(BS(x) \otimes_R k, BS(y) \otimes_R k) \]

is an isomorphism. By Soergel’s hom formula [Soe07, Theorem 5.15] and [Soe00, Lemma 2.11.2] we know that both sides have the same (finite) dimension. Using the biadjointness of B = - one can reduce to the case when x = 0. Finally, in this case it is not difficult to check that \( \phi \) is injective, and hence is an isomorphism. \( \square \)

4. PROOF OF THE THEOREM

Let W denote the symmetric group on \( \{1, 2, \ldots, a+n+b\} \) with Coxeter generators \( S = \{s_1, s_2, \ldots, s_{a+n+b-1}\} \) the simple transpositions. Given a subset \( I \subset S \) let \( W_I \) denote the corresponding standard parabolic subgroup. Consider the sets

\[ A = \{s_1, s_2, \ldots, s_{a+1}\}, M = \{s_{a+1}, \ldots, s_{a+n-1}\}, B = \{s_{a+n+1}, \ldots, s_{a+n+b-1}\}. \]

Then \( W_A \) (resp. \( W_M \), resp. \( W_B \)) is the subgroup of permutations of \( \{1, \ldots, a\} \) (resp. \( \{a+1, \ldots, a+n\} \), resp. \( \{a+n+1, \ldots, a+n+b\} \)).

We use the notation of \( \mathbf{[1]} \) except we shift all indices by a. That is we regard \( S_n \) as embedded in \( S_{a+n+b} \) as the standard parabolic subgroup \( W_M \). We rename \( R = \mathbb{Z}[x_1, \ldots, x_{a+n+b}] \) and write \( \alpha_i = x_i - x_{i+1} \) for the simple root corresponding to \( s_i \). Fix

\[ C = \partial_{w_m}(x_{a+1}x_{a+2}\partial_{w_m-1}x_{a+n}\ldots\partial_{w_1}(x_{a+1}x_{a+n})\ldots) \]

which we assume is a non-zero integer. (Now \( w_1, \ldots, w_m \in W_M \) and the fact that \( C \) is a non-zero integer implies that \( \sum \ell(w_i) = a + b \).

Let \( M' = M \setminus \{s_{a+1}, s_{a+n-1}\} \). Then for any \( w \in W_{M'} \), \( \partial_w \) commutes with the operators of multiplication by \( x_{a+1} \) and \( x_{a+n} \). Hence we may (and do) assume that each \( w_i \) is of minimal length in its coset \( w_iW_{M'} \).

Fix a reduced expression \( w_M \) for \( w_M \) and reduced expressions \( w_i \) for each \( w_i \). Let \( w \) be the sequence

\[ w = w_nw_{n-1}w_{n-2}\ldots w_2w_1w_1w_1 \]

where

\[ w_1 = (s_a \ldots s_{a-a_1+1})(s_a) \]
\[ w_2 = (s_a \ldots s_{a-a_1-a_2+1})(s_a \ldots s_{a-a_2-a_1+1})(s_a \ldots s_{a-a_1}) \]
\[ \vdots \]
\[ w_{n-1} = (s_a \ldots s_1)(s_a \ldots s_{a-1} \ldots s_{a-1-1})(s_a \ldots s_{a-1-1-1}) \]

(subscripts fall by 1 within each parenthesis, and \( s_a \) occurs \( a_i \) times in \( w_i \) and

\[ w_1 = (s_{a+n} \ldots s_{a+n+b_1-1})(s_{a+n}) \]
\[ w_2 = (s_{a+n} \ldots s_{a+n+b_1+b_2-1})(s_{a+n} \ldots s_{a+n+b_1+1})(s_{a+n} \ldots s_{a+n+b_1}) \]
\[ \vdots \]
\[ w_n = (s_{a+n} \ldots s_{a+n+b_n-1})(s_{a+n} \ldots s_{a+n+b_1+b_2+\ldots+b_{m-1}}) \]

(subscripts rise by 1 within each parenthesis, and \( s_{a+n} \) occurs \( b_i \) times in \( w_i \)).
Lemma 4.1. \( w \) is reduced.

Proof. It is routine but tedious to draw a picture of \( w \) and convince oneself that it is reduced, using that each \( w_i \) is minimal in \( w_i W_M \). \( \square \)

Remark 4.2. In fact Lemma 4.1 is not necessary for the main theorem, as it is enough to demonstrate an intersection form equal to \((\pm C)\) associated to any expression \( w \), reduced or not.

Set \( I = A \cup M \cup B \) and let \( w_I \) be its longest element. Write \( w = s_{i_1} \ldots s_{i_n} \).

Lemma 4.3. Any subexpression \( e \) of \( w \) with \( w^e = w_I \) has \( e_j = 0 \) if \( s_{i_j} \in \{ s_a, s_{a+n} \} \) and \( e_j = 1 \) if \( s_{i_j} \in A \cup B \).

Proof. Let \( e \) denote a subexpression of \( w \) with \( w^e = w_I \).

Any expression \( y \) for \( w_A \) contains a subexpression of the form \( s_{a-1}s_{a-2} \ldots s_1 \) (think about what happens to 1 \( \in \{ 1, \ldots, a \} \)). In \( w \), \( s_1 \) only occurs once. Left of \( s_1 \) there is only one occurrence of \( s_{a-1}, s_{a-2}, \) etc. We conclude that the restriction of \( e \) to \( (s_1 s_2 \ldots s_{a-1}) \) in \( w_m \) is equal to \((01 \ldots 11)\). Now any expression for \( w_A \) starting in \( s_{a-1} \ldots s_1 \) has to contain a subexpression to the right of the form \( s_{a-1} \ldots s_2 \) (think about what happens to 2 \( \in \{ 1, \ldots, a \} \)). Continuing in this way we see that the restriction of \( e \) to each \( w_i \) has the form

\[
(01 \ldots 1) \ldots (01 \ldots 1)(01 \ldots 1).
\]

Similar arguments apply to each \( w_i \) and the result follows. \( \square \)

Lemma 4.4. There is a unique subexpression \( e \) of \( w \) such that \( w^e = w_I \) and \( e \) has defect zero.

Proof. By the previous lemma we must have \( e_j = 0 \) (resp. 1) if \( s_{i_j} \in \{ s_a, s_{a+n} \} \) (resp. \( s_{i_j} \in W_{A \cup B} \)). Because each \( e_j \) with \( s_{i_j} \in \{ s_a, s_{a+n} \} \) is \( U_0 \) and because \( W_{A \cup B} \) and \( W_M \) commute we only have to understand subexpressions of

\[
w' = w_m w_{m-1} \cdots w_1 w_M
\]

of defect \(-(a+b) = - \sum_{i=1}^m \ell(w_i)\). Now it is easy to see that the only subexpression of \( w' \) fulfilling these requirements is

\[
(0 \ldots 0)(0 \ldots 0) \ldots (0 \ldots 0)(1 \ldots 1).
\]

Recall that the intersection form associated to \( w \) at \( w_I \) in degree 0 is given by pairing light leaves maps of defect zero. By the above lemma there is only one subsequence of defect zero, and hence the intersection form is a \( 1 \times 1 \) matrix. The following lemma calculates this matrix:

Lemma 4.5. The intersection form of \( w \) at \( w_I \) is \((\pm C)\).

Proof. Note that the light leaves map corresponding to the unique defect 0 subexpression \( e \) of \( w \) is simple: the last terms corresponding to \( w_M \) are \( U_1 \) and all \( e_j \) with \( s_j \in \{ s_{a+1}, \ldots, a_{a+n-1} \} \) before that are \( D_0 \); all \( e_j \) with \( s_j \in \{ s_a, s_{a+n} \} \) are \( U_0 \); and all other \( e_j \) (corresponding to simple reflections in \( A \cup B \)) are \( U_1 \). We may
picture the pairing of the light leaves with itself schematically as follows:

Here $\beta$ denotes a morphism composed entirely of braid relations (2m-valent vertices in the terminology of [EWb]), blue lines indicate simple reflections belonging to the set $M$, $\alpha$ stands for either $\alpha_a$ or $\alpha_{a+n}$ and red lines stand for simple reflections belonging to $A \cup B$.

Every time we move an $\alpha$ through a red line we apply the nil Hecke relation:

\[
j \alpha = s_j(\alpha) + \partial_j(\alpha)
\]

However the expression in the red lines is reduced. Hence the second term (with the broken line) always contributes zero to the intersection form (it belongs to the ideal $D \not\supset w_I$). Hence we can ignore the red lines if we replace each occurrence of $\alpha$ by $w(\alpha)$ for some $w \in W_{A \cup B}$. Any such $w(\alpha)$ is of the form

\[
w(\alpha) = \alpha + \sum_{j \in A \cup B} \lambda_j \alpha_j.
\]

Each $\alpha_j$ with $j \in A \cup B$ is invariant under $W_M$ and hence if we apply the nil Hecke relation again we can slide all such terms outside all blue lines. Any diagram with a positive degree polynomial on the left or right is necessarily zero (because $\text{End}_{\geq w_I}(w_I) = R$ is concentrated in non-negative degrees). Hence we can replace each $w(\alpha)$ by $\alpha$. We conclude that we can simply ignore the red lines in the above picture.

Now, when moving the left most power of $\alpha$ through a blue line it must break. We conclude that the value of the intersection form is

\[
C' = \partial_{w_m}(\alpha_a^{a_m-a+n} \partial_{w_{m-1}}(\alpha_{a_m-a+n}^{a_m-1} \partial_{w_1}(\alpha_{a_m}^{a_m-1} \alpha_{a+n}^{b_n} \ldots)\ldots)).
\]

Finally, $\alpha_a = x_a - x_{a+1}$ and $\alpha_{a+n} = x_{a+n} - x_{a+n+1}$. Because $x_a$ and $x_{a+n+1}$ commute with $W_M$ we can apply the argument of the previous paragraph to get

\[
C' = \partial_{w_m}((-x_{a+1})^{a_m-x_{a+n}} \partial_{w_{m-1}}((-x_{a+1})^{a_m-1} \partial_{w_1}((-x_{a+1})^{a_1} \ldots)\ldots)) = (-1)^a C.
\]

5. (Counter)-examples

We use the notation of §1.2.

5.1. $n < 4$: One checks easily using (1.1) and (1.2) that for $n = 2, 3$ one can only obtain $C = \pm 1$. 
5.2. $n = 4$: Using \textbf{[1.1]} and \textbf{[1.2]} we see that
\[ Y = x_1(\partial_1(x_2^2X_{\text{id}})) = X_{12} + X_{21}. \]
Now consider the operator $F : H \rightarrow H$ given by
\[ F(h) = \partial_{13}(\omega_{13}\partial_{12}(\omega_{13}h)). \]
where $\omega_{13} = x_1(-x_4)$. Using \textbf{[1.1]} and \textbf{[1.2]} (Figure 1 might be helpful) one checks easily that $X_{32}, X_{13}$ and $X_{12}$ are in the kernel of $F$, that $F$ preserves the submodule $ZX_{21} \oplus ZX_{23}$ and that in this basis $F$ is given by the matrix
\[ F = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}. \]
This matrix determines the Fibonacci recursion! Hence for $i \geq 1$ we have
\[ F^i(x_1(\partial_1(x_2^2X_{\text{id}}))) = F^iY = F_{i+1}X_{21} + F_{i}X_{23}. \]
where $F_1 = 1$, $F_2 = 1$, $F_3 = 2$, $F_4 = 3$ etc. denote the Fibonacci numbers.

We conclude from the main theorem that the Fibonacci numbers $F_{i+1}$ and $F_i$ occur as torsion in $SL_{4i+7}$. (For example $\partial_{12}(F^i(x_1(\partial_1(x_2^2)))) = F_{i+1}$. ) By Carmichael’s theorem \cite{Car14} the first $n \gg 0$ Fibonacci numbers have at least $n$ distinct prime factors. Now by the prime number theorem we conclude that the torsion in $SL_n$ grows at least as fast as some constant times $n \log n$. Hence no linear bound is sufficient for Lusztig’s conjecture.

$n = 5$: In the following table we list some examples of torsion in $SL_N$ found using the $SL_5$ flag variety. The entries in the list were found by random computer searches, and are probably not optimal.

| $N$ | 10 | 14 | 16 | 18 | 20 | 22 | 26 | 30 | 34 | 38 | 40 | 100 | 200 |
|-----|----|----|----|----|----|----|----|----|----|----|----|-----|-----|
| $p$ | 3  | 7  | 13 | 23 | 43 | 61 | 139| 421| 839| 1867| ... | 5674199 | 1225837367 |

6. \textbf{JAMES CONJECTURE}

In this section we indicate why the results of the previous section yield counterexamples to the James conjecture \cite{Jam90} on the decomposition numbers of Schur algebras and the symmetric group.

Fix positive integers $N$ and $r$. Let $\Lambda^+(N, r)$ denote the set of partitions of $r$ into at most $N$ parts; that is, sequences $(\lambda_1, \ldots, \lambda_N)$ such that $\lambda_1 \geq \cdots \geq \lambda_N \geq 0$ with...
$r = \sum \lambda_i$. Then $\Lambda^+(N, r)$ is a partially ordered set with respect to the dominance order $\leq$.

Let $S(N, r)$ denote the Schur algebra over $\mathbb{Z}$ (see e.g. [Gre81]). Its category of representations is equivalent to the category of polynomial representations of the group scheme $GL_N$ of fixed degree $r$. Fix a field $k$ of characteristic $p > N$ and let $S_k(N, r)$ denote the Schur algebra over $k$. The category $\text{Rep}_{S_k}(N, r)$ of finitely generated $S_k(N, r)$-modules is a highest weight category with simple modules indexed by $\Lambda^+(N, r)$. Given $\lambda \in \Lambda^+(N, r)$ we denote by $L(\lambda)$ (resp. $\Delta(\lambda)$, $\nabla(\lambda)$, $P(\lambda)$, $T(\lambda)$) the simple (resp. standard, costandard, indecomposable projective, indecomposable tilting) module indexed by $\lambda$.

Let $S_q(N, r)$ denote the $q$-Schur algebra and $S_e(N, r)$ its specialisation at a fixed primitive $p$th-root of unity $\varepsilon \in \mathbb{C}$ (see e.g. [Dou98]). Then the category of finitely generated $\text{Rep}_{S_e}(N, r)$-modules is highest weight. As above we write $L_e(\lambda)$ (resp. $\Delta_e(\lambda)$ etc.) for the simple (resp. standard etc.) module corresponding to $\lambda \in \Lambda^+(N, r)$. Given a module $M$ for $S_e(N, r)$ we may choose a stable $\mathbb{Z}[\varepsilon]$-lattice and reduce to obtain a module over $S_q(N, r)$. In this way we obtain the decomposition map on Grothendieck groups

$$d : [\text{Rep}_{S_e}(N, r)] \to [\text{Rep}_{S_k}(N, r)].$$

One has $d([\nabla_e(\lambda)]) = [\nabla(\lambda)]$. The James conjecture [Jam90] predicts that

$$d([L_e(\lambda)]) = [L(\lambda)]$$

if $p > \sqrt{r}$.

Let $\rho = (N-1, \ldots, 1, 0) \in \Lambda^+(N, \binom{N}{2})$ and let $st := (p-1)\rho$ denote the “Steinberg weight”. Let $S_N$ denote the symmetric group of $N$ letters, acting by permutation on $\mathbb{Z}^N$. Lusztig’s character formula gives (see [3.1] for notation)

$$\nabla_e(st + x\rho) : L_e(st + y\rho) |_{x,y} = h_{x,y}(1).$$

as modules for $S_e(N, p\binom{N}{2})$. (Actually, Lusztig’s character formula gives the multiplicity for the quantum group of $\mathfrak{sl}_N$ specialised at $\varepsilon$ in terms of an affine Kazhdan-Lusztig polynomial. The translation of his formula to yield the above multiplicity is standard but technical. Alternatively, one can appeal to [LJS94] and the $p \gg 0$ version of (6.3) below.)

Similarly, [Soe04, Theorem 1.2.2] gives (again see (3.1) for notation)

$$\nabla(st + x\rho) : L(st + y\rho) |_{x,y} = h_{x,y}(1)$$

as modules for $S_k(N, p\binom{N}{2})$. (Actually, Soergel’s result gives this multiplicity for rational modules for $SL_N(k)$. The translation to $GL_N$ and hence to modules for the Schur algebra is standard.)

We conclude that whenever $pH_x \neq H_x$ for some $x$ the characters of the simple modules for $S_e(N, p\binom{N}{2})$ and $S_k(N, p\binom{N}{2})$ are different, because the simple and costandard modules both give bases for the Grothendieck group. In particular, there exists $\lambda$ such that $d([L_e(\lambda)]) \neq [L(\lambda)]$. Hence any $p$ appearing on the table in Section 3 with $p > \binom{N}{2}$ contradicts the the James conjecture for $S(N, p\binom{N}{2})$.

\footnote{A stronger version requires that $p$ be larger than the weight of $\lambda$. It reduces to the condition $\sqrt{r}$ for the principal block, which will be the only case considered below.}
shows that restricted (Remark 6.1) decomposition numbers are invisible to the symmetric group, as all simples corresponding to non $p$-restricted weights are killed by the Schur functor.

However, amongst weights of the form $st + x\rho$ for $x \in S_N$ only $st + w_0\rho$ is $p$-restricted ($w_0$ denotes the longest element of $S_N$). Hence the above non-trivial decomposition numbers are invisible to the symmetric group, as all simples corresponding to non $p$-restricted weights are killed by the Schur functor.

The get counter-examples in the symmetric group we can use the Ringel self-duality of the Schur algebra and modular category $O$. (I thank Joe Chuang for explaining this to me.) Given any $N' \geq N$ we have an obvious embedding $\Lambda^+(N, r) \hookrightarrow \Lambda^+(N', r)$ obtained by appending 0's to the partition. There is a quotient functor $f : \text{Rep} S(N', r) \to \text{Rep} S(N, r)$ which preserves simple, standard, costandard modules and indecomposable tilting modules corresponding to $\lambda$ in $\Lambda^+(N, r) \subseteq \Lambda^+(N', r)$ (see [Gre81, §6.5] and [Don92, A.4.5]).

Now consider modular category $O$ [Soc01, §2.3]. It is defined as the Serre sub-quotient $O := \mathcal{A}/N$ of $\text{Rep} S_N(N, p(n))$ where $\mathcal{A}$ is the Serre subcategory generated by simple modules $L(\lambda)$ such that $\lambda \leq st + \rho$ and $\lambda$ lies in the same block as $st + \rho$, and $N$ denotes the Serre subcategory generated by those simples $L(\lambda) \in \mathcal{A}$ which are not of the form $L(st + x\rho)$ for some $x \in S_N$. The definition of $O_\varepsilon$ is obtained by replacing $L(\lambda)$ by $L_\varepsilon(\lambda)$ in the definition of $O$.

Let us denote the images of $L(st + x\rho)$, $\Delta(st + x\rho)$, etc., in $O$ as $L(x)$, $\Delta(x)$, etc. and similarly for $O_\varepsilon$. Then $O$ is a highest weight category with simple, standard, etc. and tilting objects $L(x)$, $\Delta(x)$, etc., and similarly for $O_\varepsilon$. It is known that both categories are Ringel self-dual. (The proof of this fact seems not to be explicit in the literature. However a proof may be obtained by adapting ideas of [BBM04]. One shows that one has a braid group action on $D^b(O)$ (resp. $D^b(O_\varepsilon)$) and a lift of the longest element interchanges a projective and tilting generator.) Applying BGG reciprocity then Ringel self-duality for $O$ and $O_\varepsilon$ we obtain:

$$h_{x,y}(1) = \nabla(\Delta, \nabla, \varepsilon(x) : L(\Delta, \nabla, \varepsilon(y)) = (P_\varepsilon(y) : \Delta_\varepsilon(x)) = (T_\varepsilon(yw_0) : \nabla_\varepsilon(xw_0)),
$$

$$p h_{x,y}(1) = \nabla(\nabla, \Delta, \varepsilon(x) : L(\nabla, \Delta, \varepsilon(y)) = (P(y) : \Delta(x)) = (T(yw_0) : \nabla(xw_0)).$$

Applying Ringel self-duality of the Schur algebra $S(p(N^2_2), p(N^2_2))$ [Don93] we have:

$$h_{x,y}(1) = (T_\varepsilon(st + yw_0\rho) : \nabla_\varepsilon(st + xw_0\rho)) = (P_\varepsilon((st + yw_0\rho)') : \Delta_\varepsilon((st + xw_0\rho)')), p h_{x,y}(1) = (T(st + yw_0\rho) : \nabla(st + xw_0\rho)) = (P((st + yw_0\rho)') : \Delta((st + xw_0\rho)')$$.

Finally, again by BGG reciprocity

$$h_{x,y}(1) = \nabla_\varepsilon((st + xw_0\rho)' : L_\varepsilon((st + yw_0\rho)'),
$$

$$p h_{x,y}(1) = \nabla_\varepsilon((st + xw_0\rho)' : L_\varepsilon((st + yw_0\rho)').$$

The partitions $(st + xw_0\rho)'$ and $(st + yw_0\rho)'$ are $p$-restricted. Hence, after applying the Schur functor the first (resp. second) number can be interpreted as a decomposition number for the Hecke algebra specialized at $\varepsilon$ (resp. the symmetric group in characteristic $p$). It follows that the results of the previous section also produce counter-examples for the symmetric group.
Remark 6.2. Consulting the table of counter-examples in Section 6 we see that the smallest counter-example produced by the above methods occurs in $S_{N'}$ with

$$N' = p \left( \frac{N}{2} \right) = 839 \left( \frac{34}{2} \right) = 467874.$$ 

The size of this number is a relic of our method (in particular the fact that we cannot say anything about $p$-restricted weights). It is an important open question as to where the first counter-examples occur.

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