Generalised Burnside rings, $G$-categories and module categories

by

Paul Gunnells
Andrew Rose
Dmitriy Rumynin
Generalised Burnside rings, $G$-categories and module categories

Paul Gunnells
Andrew Rose
Dmitriy Rumynin

Max-Planck-Institut für Mathematik
Vivatsgasse 7
53111 Bonn
Germany

Department of Mathematics and Statistics
University of Massachusetts
Amherst, MA 01003
USA

Department of Mathematics
University of Warwick
Coventry CV4 7AL
UK
GENERALISED BURNSIDE RINGS, $G$-CATEGORIES AND MODULE CATEGORIES

PAUL GUNNELLS, ANDREW ROSE, AND DMITRIY RUMYNIN

ABSTRACT. This note describes an application of the theory of generalised Burnside rings to algebraic representation theory. Tables of marks are given explicitly for the groups $S_4$ and $S_5$ which are of particular interest in the context of reductive algebraic groups. As an application, the base sets for the nilpotent element $F_4(a_3)$ are computed.

Our aim is to combine two modern lines of enquiry. The first line is generalised Burnside rings which were recently introduced by Hartmann and Yalçın [10]. The second line is the study of tensor categories attached to cells in affine Weyl groups by Bezrukavnikov, Finkelberg and Ostrik [3, 1]. We show how one can use generalised Burnside rings to carry through explicit calculations with module categories.

The note is organised as follows. In section 1 we introduce generalised Burnside rings. Our generalised Burnside ring is slightly more general than the one of Hartmann and Yalçın. We define it for a general functor rather than the cohomology functor. For our applications, the most crucial functor is the Schur multiplier $\mu(G)$, so we describe the table of marks for the Schur multiplier for the symmetric groups $S_4$ and $S_5$. In section 2 we discuss the connection between $\mu$-decorated sets and $G$-algebras. In section 3 we discuss the connection between $\mu$-decorated sets and groupoids. In section 4 we discuss module categories in the spirit of Bezrukavnikov and Ostrik [3]. In section 5 we discuss based sets of Kazhdan-Lusztig cells [13]. We use computer calculation with Kazhdan-Lusztig polynomials and a pen-and-paper calculation in the Burnside ring of $S_4$ to determine the base set of the largest finite double cell in the affine Weyl group of the type $F_4$.

In the final section 6, we discuss an application to representation theory of the reduced enveloping algebra $U_\chi(g)$ where $g$ is of the type $F_4$ and $\chi$ is of the type $F_4(a_3)$.

The authors would also like to thank M. Belolipetsky, M. Finkelberg, S. Goodwin, J. Humphreys, G. Rohrle and W. Soergel for stimulating discussions.

1. Generalised Burnside ring

Let $G$ be a finite group, $S(G)$ its category of subgroups. Objects of $S(G)$ are subgroups of $G$. The morphisms $S(A,B)$ are conjugations $\gamma_x : A \to B$, $\gamma_x(a) = xax^{-1}$, $x \in G$ whenever $xAx^{-1} \subseteq B$, restricted to $A$. Thus, $\gamma_x$ and $\gamma_y$ define the same morphism in $S(A,B)$ whenever $y^{-1}x$ is in the centraliser of $A$. The composition of morphisms is the composition of homomorphisms.

A generalised Burnside ring $B^G_F(G)$ depends on a contravariant functor $\Phi$ from $S(G)$ to the category of semigroups and a commutative ring of coefficients $R$. As an $R$-module it is generated by disjoint union of $\Phi(A), A \in S(G)$. We write $\langle a, A \rangle$ for an element of the semigroup $a \in \Phi(A)$. The $R$-module generators satisfy the relations

$$\langle a, A \rangle = \langle \Phi(\gamma_g)(a), g^{-1}Ag \rangle$$

for all $g \in G, A \in S(G), a \in \Phi(A)$. Notice that $\langle a, A \rangle + \langle b, A \rangle \neq \langle ab, A \rangle$ in general (we think of semigroups as multiplicative semigroups). The multiplication is $R$-bilinear, defined on the $R$-module generators by the formula

$$\langle a, A \rangle \cdot \langle b, B \rangle = \sum_{A_x B \in A \setminus G/B} \langle \Phi(\gamma_1 : A \cap xBx^{-1} \to A)(a)\Phi(\gamma_{x^{-1}} : A \cap xBx^{-1} \to B)(b), A \cap xBx^{-1} \rangle.$$
Lemma 1.1. Defined as above, $\mathbb{B}_R^\Phi(G)$ is an associative $R$-algebra. If $\Phi$ is a functor to monoids then $\mathbb{B}_R^\Phi(G)$ is unitary.

Proof. A sleek way to prove this is to interpret $\mathbb{B}_R^\Phi(G)$ as a Grothendieck group of $\Phi$-decorated $G$-sets. A $\Phi$-decorated $G$-set is a finite set $X$ with a $G$-action and a frill $\pi_x \in \Phi(G_x)$ attached to each point $x \in X$. Here $G_x$ is the stabiliser of $x$ in $G$. The frills $\pi_x$ must be equivariant in a sense that $\pi_{gx} = \Phi(\gamma_g)(\pi_x)$.

The element $\langle a, A \rangle$ represents a homogeneous set $G/A$ with frills $\pi_{gA} = \Phi(\gamma_g)(a)$. The addition corresponds to disjoint union $[X] + [Y] = [X \coprod Y]$ and the multiplication corresponds to the direct product $[X] \cdot [Y] = [X \times Y]$, where the frills multiplied in the corresponding semigroup (note that $G(x, y) = G_x \cap G_y$):

$$\pi_{(x, y)} = \Phi(\gamma_1 : G(x, y) \to G_x)(\pi_x) \Phi(\gamma_1 : G(x, y) \to G_y)(\pi_y).$$

If $\Phi$ is a functor to monoids, then $\langle 1, G \rangle$ is the identity of $\mathbb{B}_R^\Phi(G)$ as can be easily verified. 

The subgroup category $\mathcal{S}(G)$ is an example of a fusion system. Burnside rings of fusion systems were constructed by Diaz and Libman [6]. Generalised Burnside rings can be extended to fusion systems as well.

An interested reader is invited to follow this lead, especially if the reader can think of useful applications.

The notion of a mark homomorphism can be extended to generalised Burnside rings (cf. [10, §6]). Let $S$ be an associative $R$-algebra and $\alpha : \Phi(A) \to S^\times$ is a semigroup homomorphism for some $A \in \mathcal{S}(G)$. The corresponding mark is an $R$-linear map $f_A^\alpha : \mathbb{B}_R^\Phi(G) \to S$ given by the formula

$$f_A^\alpha((b, B)) = \frac{1}{|B|} \sum_{g \in X} \alpha(\Phi(\gamma_g : A \to B))(b)$$

where $X = \{ g \in G \mid gAg^{-1} \subseteq B \}$.

Lemma 1.2. The mark $f_A^\alpha$ is an $R$-algebra homomorphism. It is unitary if $\Phi$ is a functor to monoids and $\alpha$ is unitary.

Proof. Let us reinterpret the mark using $\Phi$-decorated sets. The condition $gAg^{-1} \subseteq B$ means that $Ag^{-1}B = g^{-1}B$, i.e., $A$ lies in the stabiliser of $g^{-1}B$. The frill of $X$ with $[X] = \langle b, B \rangle$ at $g^{-1}B$ is $\Phi(\gamma_g)(b)$. Thus, on the level of decorated sets,

$$f_A^\alpha([X, \pi_x]) = \sum_{x \in X^A} \alpha(\Phi(\gamma_1 : A \to G_x)(\pi_x))$$

and, consequently,

$$f_A^\alpha([X, \pi_x] \times (Y, \psi_y)) = \sum_{(x, y) \in (X \times Y)^A} \alpha(\Phi(\gamma_1 : A \to G_x)(\pi_x) \Phi(\gamma_1 : A \to G_y)(\psi_y)) = \sum_{x \in X^A} \sum_{y \in Y^A} \left( \alpha(\Phi(\gamma_1 : A \to G_x)(\pi_x)) \right) \left( \alpha(\Phi(\gamma_1 : A \to G_y)(\psi_y)) \right) = f_A^\alpha(X, \pi_x) f_A^\alpha(Y, \psi_y).$$

In the unitary case, the identity of $\mathbb{B}_R^\Phi(G)$ is $\langle 1, G \rangle$ and $f_A^\alpha((1, G)) = \alpha(\Phi(\gamma_1)(1)) = \alpha(1_{\Phi(A)}) = 1_S$.

Note that if $\Phi(A)$ is a finite abelian group there is an isomorphism between the group of linear characters of $\Phi(A)$ and the group $\Phi(A)$. If all $\Phi(A)$ are finite abelian groups then the number of distinct marks is equal to the rank of $\mathbb{B}_R^\Phi(G)$ over $R$. Let us formulate this as a corollary.

Corollary 1.3. Suppose all $\Phi(A)$ are finite abelian groups, $N$ the least common multiple of all the orders of elements in all $\Phi(A)$. If $R$ is a field containing primitive $N$-th root of unity then the mark homomorphisms define an isomorphism $\mathbb{B}_R^\Phi(G) \to \oplus R$.

Before formulating the next property, let us introduce the notion of the dual set. Let $Y$ be a $\Phi$-decorated set such that each frill $\pi_m \in \Phi(G_m)$ is invertible. The dual set $Y^\vee$ has the same underlying $G$-set $Y$ but the frills are inverted: each $\pi_m \in \Phi(G_m)$ is replaced with $\pi_m^{-1}$.

Lemma 1.4. If $\Phi(A)$ is abelian for each $A \leq G$ then $\mathbb{B}_R^\Phi(G)$ is a commutative ring. If $\Phi(A)$ is a group for each $A \leq G$ then $\mathbb{B}_R^\Phi(G)$ is a ring with involution.

Proof. The involution is defined by $[Y]^\vee := [Y^\vee]$. Now both statements follow from the definition of $\mathbb{B}_R^\Phi(G)$. 

2
If \( R = \mathbb{Z} \), we write \( \mathbb{B}^\Phi(G) \) for \( \mathbb{B}^\Phi_R(G) \). Several functors \( \Phi \) are interesting for applications. First of all, the trivial functor \( \Phi(H) = \{1\} \) gives the classical Burnside ring \( \mathbb{B}(G) \), the Grothendieck ring of finite \( G \)-sets. Another interesting functor is \( \Phi(H) = \text{Rep}_H(H) \), the effective part of the representation ring of \( H \) over \( \mathbb{Z} \). It has two different semigroup structures, corresponding to tensor products or direct sums of representations. The corresponding Burnside ring \( \mathbb{B}^\Phi(G) \) is the Grothendieck ring of pairs \((X,V)\), a finite \( G \)-set and a \( G \)-equivariant vector bundle on it. One can consider the effective part of Burnside ring itself \( \Phi(H) = \mathbb{B}_+^\Phi(H) \). Again it has two different semigroup structures, corresponding to products or unions. The corresponding Burnside ring \( \mathbb{B}^\Phi(G) \) is the Grothendieck ring of fibred \( G \)-sets \( Y \to X \), i.e. surjective maps of \( G \)-sets, where one considers \( Y \) as an equivariant fibration over \( X \). Hartmann and Yalçın has studied \( \Phi(H) = H^*(H,M) \) or \( \Phi(H) = H^n(H,M) \), where \( M \) is a \( G \)-module [10]. They have called the corresponding \( \mathbb{B}^\Phi(G) \) a cohomological Burnside ring.

The second cohomological Burnside ring is of particular interest to us. It will be studied for the rest of the paper. Namely, if \( K \) is a field, we need the functor \( \mu_K(H) = H^2(H,K) \) where \( H \) acts trivially on the multiplicative group \( K^\times \) of the field. As soon as \( K^\times \) has enough torsion, say \( K \) admits a \( |G| \)-th primitive root of 1 (for instance, if \( K \) is algebraically closed of characteristic \( p \) not dividing \( |G| \)), \( \mu_K(H) \) is the Schur multiplier of \( H \) [12]. In particular, it is independent of \( K \) and will be denoted just \( \mu(H) \) with the corresponding Burnside ring \( \mathbb{B}^\mu(G) \).

We present the tables of marks for \( \mathbb{B}^\mu(G) \) of the symmetric groups \( S_4 \) and \( S_5 \) in Tables 1 and 2. We use the notation \( \langle K \rangle = \{1,K\} \), \( \langle K' \rangle = \{x,K\} \) where \( x \) is a generator of \( C_2 \), the only possible nontrivial \( \mu(H) \), and \( f'_H \) is a mark with nontrivial character of \( C_2 \). In these tables \( D_8 \) and \( D_{30} \) denote the standard dihedral groups of orders \( 8 \) and \( 10 \), \( K_1 = \langle (12), (34) \rangle \) and \( K_2 = \langle (12)(34), (13)(24) \rangle \) denote nonconjugate Klein four groups, \( C_n \) denotes a cyclic subgroup of order \( n \) generated by a single cycle. Notation \( H \mu \) is reserved for various non-standard subgroups of order \( n \): \( H_2 \) is generated by \( (1,2)(3,4) \), \( S_5 \) has \( H_20 \) and \( H_6 \), the normaliser of \( C_5 \) and the nonstandard symmetric group on 3 elements \( ((123), (12)(45)) \). The columns of the tables correspond to values of the marks \( f_H \) or \( f'_H \) with the nontrivial character of \( C_2 \) ordered as for the rows. Appeared to the tables are the values of the function \( M : \mathbb{B}^\mu(G) \to \mathbb{Z} \) that can be thought of as an equivariant Euler characteristic of the extended \( G \)-set. It will be discussed in Section 4. Notice that any field of characteristic not 2 will give the same table of marks.

The tables were computed by lifting data from the ordinary table of marks and the following lemma.

**Lemma 1.5.** Let \( H \leq K \leq G \), and \(|G| \) invertible in \( K \). Suppose that \(|\mu(K)| = |\mu(H)| = 2 \) and 2 does not divide the index \(|K:H|\). Then \( f'_H(\langle K' \rangle) = -f_H(\langle K \rangle) \).

**Proof.** Let \( \tau \in \mu(K) \) and \( \nu \in \mu(H) \) be non-trivial cocycles. The corestriction map on cocycles satisfies \( \text{res}_{K,H}(\text{cor}_{H,K}(\nu)) = |K:H|\nu \) [12, Ch. 1]. Thus, \( \text{res}_{K,H}(\text{cor}_{H,K}(\nu)) = \nu \). Therefore \( \nu \) corestricts to the nontrivial cocycle \( \tau \) and \( \text{res}_{K,H}(\tau) \neq 1 \). The lemma now follows from Equation (1). \( \square \)

## 2. \( G \)-algebras and \( \mu_K \)-decorated sets

A \( G \)-algebra is an associative algebra \( A \) with a (left) action of \( G \). As a default option, an action is always a left action. However, right actions often appear naturally. For instance, the group \( G \) acts (on the right) on the abelian category \( A \to \text{Mod} \) of left \( A \)-modules.

We say that \( G \) has a right action on a category \( C \) if for every \( g \in G \), we have an autoequivalence, \( [g] : C \to C \), together with natural isomorphisms \( \gamma_{g,h} : [g] \circ [h] \to [hg] \) such that \([1] \) is the identity functor. In this case, we call \( C \) a \( G \)-category.

Sometimes in the literature such actions are called “weak” as opposed to “strong” actions, which satisfy commutativity of the associativity constraint diagrams

\[
\begin{array}{ccc}
[f] \circ [g] \circ [h] & \xrightarrow{\gamma_{f,g}} & [g] \circ [hf] \\
\downarrow_{\gamma_{g,h}} & & \downarrow_{\gamma_{hf,h}} \\
[f] \circ [hg] & \xrightarrow{\gamma_{f,hg}} & [hf] \\
\end{array}
\]

for all \( f,g,h \in G \). We do not use the term “weak” since we are not interested in associativity constraints.

Let us describe \([g]\) and \( \gamma_{g,h} \) for \( C = A \to \text{Mod} \), in detail. On objects, \( M^{[g]} = M \) with the new action of \( A \) given by \( a \cdot [g] m = g(a)m \). On morphisms, \( f^{[g]} = f \). Finally, for each object \( M \), \( \gamma_{g,h}(M) : (M^{[h]})^{[g]} \to M^{[hg]} \)

3
is the identity map. Notice that \( a \cdot [h][g] \cdot m = g(a) \cdot [h] \cdot m = h(g(a))m = a \cdot [hg] \cdot m \). Notice further that this action is strong.

Going back to a general \( G \)-category, we say that an object \( X \) is **equivariant** if all its twists \( X[g] \) are isomorphic to \( X \) and there exists a system of isomorphisms \( \alpha_g : X \to X[g] \) such that the diagrams

\[
X \quad \xrightarrow{\alpha_h} \quad X[h]
\]

\[
X[g] \quad \xrightarrow{\gamma_{g,h}(X)} \quad X[g][h]
\]

are commutative for all \( g, h \in G \). This notion allows us to characterise \( A \ast G \)-modules among \( A \)-modules where \( A \ast G \) is the skew group algebra, i.e. a free left \( A \)-module with a basis \( G \) and a multiplication coming from those of \( A \) and \( G \) with an additional rule \( ga = g(a)g \) for all \( a \in A, g \in G \).

**Lemma 2.1.** An \( A \)-module \( M \) is an equivariant object of \( A - \text{Mod} \) if and only if it admits a structure of an \( A \ast G \)-module.

**Proof.** The connection between the equivariant structure and the action of \( G \) is given by \( \alpha_g(m) = g \cdot m \). One can verify that the axioms of both structures are equivalent. \( \square \)

A functor \( \Phi : \mathcal{C} \to \mathcal{D} \) between \( G \)-categories is a **\( G \)-functor** if it is equipped with a system of natural isomorphisms \( \beta_g : \Phi \circ [g]_{\mathcal{C}} \to [g]_{\mathcal{D}} \circ \Phi, \ g \in G \) such that the square

\[
\Phi(X[g]) \quad \xrightarrow{\beta_g(X)} \quad \Phi(X)[g]
\]

\[
\Phi(\epsilon[g]) \downarrow \quad \Phi(\epsilon)[g] \downarrow
\]

\[
\Phi(Y[g]) \quad \xrightarrow{\beta_g(Y)} \quad \Phi(Y)[g]
\]

is commutative for all \( t \in \mathcal{C}(X,Y), g \in G \) and the pentagon

\[
\Phi(X)[gh] \quad \xrightarrow{\Phi(\gamma_{g,h}(X))} \quad \Phi(X)[g][h]
\]

\[
\Phi(X)[g] \quad \xrightarrow{\Phi(\beta_g(X)[g])} \quad \Phi(X)[g][h]
\]

\[
\Phi(X)[gh] \quad \xrightarrow{\gamma_{g,h}(\Phi(X))} \quad \Phi(X)[g][h]
\]

\[
\Phi(X)[gh] \quad \xrightarrow{\beta_g(\Phi(X))} \quad \Phi(X)[g][h]
\]

is commutative for all objects \( X \in \mathcal{C} \) and \( g, h \in G \). A \( G \)-equivalence is a \( G \)-functor which is an equivalence.

**Lemma 2.2.** Let \( \Phi : \mathcal{C} \to \mathcal{D} \) be a \( G \)-equivalence between \( G \)-categories. If \( X \) is a \( G \)-equivariant object in \( \mathcal{C} \) then \( \Phi(X) \) is a \( G \)-equivariant object in \( \mathcal{D} \).

**Proof.** Let \( X = (X, \alpha_g) \) be an equivariant object. The equivariant structure on \( \Phi(X) \) is given by the compositions \( \beta_g(X) \circ \Phi(\alpha_g) : \Phi(X) \to \Phi(X[g]) \to \Phi(X)[g] \). To verify the axiom we analyse the following diagram.
The following theorem characterises associative $G$-Morita equivalences within the context of Morita theory.

**Theorem 2.3.** Associative $G$-algebras $A$ and $B$ are $G$-Morita equivalent if and only if there exists a non-degenerate $G$-equivariant Morita context $(A, B, \Phi, \phi, \psi)$.

**Proof.** A non-degenerate $G$-equivariant context gives a $G$-equivalence $\Phi : A \to B$ by $\Phi(P) = N \otimes_A P$ with an inverse equivalence $T \mapsto M \otimes_B T$. The equivariant structure on $\Phi$ is given by

$$N \otimes_A P^{[g]} = (N \otimes_A P)^{[g]}, \quad n \otimes p \mapsto g \cdot n \otimes p.$$  

Commutativity of the squares and the pentagons is obvious.

In the opposite direction, let $\Phi : A \to B$ be a $G$-equivalence and $\Psi : B \to A$ its inverse $G$-equivalence. Out of this one derives a standard nondegenerate Morita context: $N = \Phi(A)$, $M = \Psi(B)$. As $A$ and $B$ are progenerators, the functor $\Phi$ is naturally isomorphic to $N \otimes_A$ and $\Psi$ is naturally isomorphic to $M \otimes_B$. The isomorphisms $\phi : M \otimes_B N \cong \Phi(\Phi(A)) \to A$ and $\psi : N \otimes_A M \cong \Phi(\Psi(B)) \to B$ come from the natural isomorphisms.

It remains to see through the action of $G$. The object $N = \Phi(A)$ is $G$-equivariant by Lemma 2.2, i.e., it is naturally a $B \otimes G$-module by Lemma 2.1. Thus, $g \cdot (bn) = (g \cdot b)(g \cdot n)$ for all $b \in B$, $g \in G$, $n \in N$. Since $\Phi$ is an equivalence of categories, $\text{End}_B(N) \cong \text{End}_A(A) \cong A$, and $N$ is a $B$-$A$-bimodule. Finally, the property $g \cdot (na) = (g \cdot n)(g \cdot a)$ for all $a \in A$, $g \in G$, $n \in N$ follows from the same property for $A$. To prove this, observe that if $R_\phi$ is a right multiplication by $\alpha$ then the property for $A$ manifests in the diagram

$$\begin{array}{cc}
A & \xrightarrow{\alpha} & A \\
\downarrow & & \downarrow \\
A & \underset{5}{\xrightarrow{R_\phi}} & A
\end{array}$$
being commutative (N.B., $A[g] = A$). Applying $\Phi$ gives commutativity of the left square in the diagram

$$
\begin{array}{ccc}
N & \Phi(\alpha_n) & N \\
\downarrow & \downarrow & \downarrow \\
N & \beta_N(N) & N
\end{array}
$$

(N.B., $\Phi(R_a) = R_a = R_a^B$). The right square is commutative by the definition of a $G$-functor. Thus, the whole diagram is commutative that manifests in $g \cdot (na) = (g \cdot n)(g \cdot a)$ for all $a, g \in G, n \in N$.

Similarly, $M = \Psi(B)$ is an $A$-$B$-module with a compatible action of $G$. The bimodule isomorphisms $\phi : M \otimes_B N \to A$ and $\psi : N \otimes_A M \to B$ come from the isomorphisms $\Psi(\Phi(A)) \cong A$ and $\Phi(\Psi(B)) \cong B$. The latter are isomorphisms of $G$-modules. Hence, so are $\phi$ and $\psi$. \hfill $\square$

Every $G$-algebra $A$ over $K$ admits a canonical $\mu_K$-decorated set $\text{Irr}(A)$ of isomorphism classes of absolutely simple $A$-modules. Recall that a simple $A$-module $M$ is absolutely simple if $\text{End}_A(M) = K$. The (left) action of $G$ on $\text{Irr}(A)$ comes from the category $A-\text{Mod}$: $g \cdot [M] = [M^{(g^{-1})}]$.

Let us observe the cocycle. Let $G_M$ be the stabiliser of $[M] \in \text{Irr}(A)$, $a \in \text{Hom}_K(A \otimes M, M)$ the $A$-action on $M$. Since $G_M$ does not change the isomorphism class of the module, $G_M a \subseteq GL(M)a$. The stabiliser of $a$ in $GL(M)$ is the group of module automorphisms of $M$, which is $K^\times$ since $M$ is absolutely irreducible. Hence, $X \nrightarrow X \cdot a$ is a bijection from the group $PGL(M)$ to the orbit $GL(M)a$. Thus, $g \mapsto g^{-1} \cdot a$ defines a natural function $\phi_M : G_M \to PGL(M)$. This function is a group homomorphism because the actions of $G_M$ and $PGL(M)$ commute. Indeed, the action of $G_M$ factors through $GL(A)$, while $GL(A)$ and $PGL(M)$ act on the different tensor components of $\text{Hom}_K(A \otimes M, M)$. Hence,

$$
\phi(gh) \cdot a = (gh)^{-1} \cdot a = h^{-1} \cdot (g^{-1} \cdot a) = h^{-1} \cdot (\phi(g) \cdot a) = \phi(g) \cdot (h^{-1} \cdot a) = \phi(g) \phi(h) \cdot a.
$$

The obstruction to lifting of $\phi_M$ to a homomorphism $G_M \to GL(M)$ is a cocycle $\theta_M \in Z^2(G_M, K^\times)$, well defined up to a coboundary. Thus, the frill $\pi_M := [\theta_M] \in \mu_K(G_M)$ and $\text{Irr}(A)$ is a $\mu_K$-decorated $G$-set, albeit it does not have to be finite for an arbitrary $A$.

**Theorem 2.4.** The function $\Upsilon([A]) = [\text{Irr}(A)]$ is a bijection from the set of $G$-Morita equivalence classes of semisimple split $G$-algebras to the set of isomorphism classes of finite $\mu_K$-decorated $G$-sets. Moreover, using the multiplication in $\mathcal{B}(G)$,

$$
\Upsilon([A \otimes B]) = \Upsilon([A])\Upsilon([B]), \quad \Upsilon([A \oplus B]) = \Upsilon([A]) + \Upsilon([B]) \quad \text{and} \quad \Upsilon([A^{op}]) = \Upsilon([A])^\vee.
$$

for all semisimple split $G$-algebras $A$ and $B$.

**Proof.** To prove bijectivity we describe the inverse function $\Upsilon^{-1}$. Let $X$ be a finite $\mu_K$-decorated $G$-set, $X_0 \subseteq X$ a set of representatives of $G$-orbits. For each point $m \in X_0$ let us choose an irreducible projective representation $V_m$ of $G_m$ that affords the frill $\pi_m$. Let $T_m$ be the right transversal of $G_m$ in $G$. Now, for each $x \in X$ there exist unique $m \in X_0, g \in T_m$ such that $x = g \cdot m$. We define a projective representation $V_x$ of $G_x$ by

$$
V_x = V_m, \quad h \cdot v := (g^{-1}hg) \cdot v, \quad \forall h \in G_x, \quad v \in V_x = V_m.
$$

The collection $\mathcal{V} = (V_x, x \in X)$ of vector spaces is a $G$-equivariant vector bundle on $X$ [3]. In plain terms, it means that there is a linear map $\Theta_x(g) : V_x \to V_{gx}$ for all $g \in G, x \in X$. To see this map, observe a bijection between $\mathcal{V}$ and the fibre product

$$
\prod_{m \in X_0} G \times G_m V_m := \prod_{m \in X_0} G \times V_m \xrightarrow{\sim} \mathcal{V}
$$

where $(g, v) \sim (g', v')$ if and only if they are in the same $G \times V_m$ and there exists $h \in G_m$ such that $g' = gh$, $v' = h^{-1} v$. Now $\Theta_x(g)[(h, v)] = [gh, v]$. Using this, we can construct a semisimple split $G$-algebra

$$
A := \oplus_{x \in X} \text{End}_K(M_x), \quad g \cdot (\alpha_x) = (\Theta_x(g)\alpha_x \Theta_{x}(g^{-1}))
$$

with $\text{Irr}(A)$ isomorphic to $X$ as $\mu_K$-decorated $G$-sets. Notice that the different choice of $X_0$ or one of $T_m$ will lead to an isomorphic algebra, while a different choice of one of $V_m$ will lead to a $G$-Morita equivalent algebra. Thus $\Upsilon$ is a bijection.
The first two properties of $\Upsilon$ are immediate. The last property follows from the fact that the simple $A^{op}$-modules are the dual spaces $M^*$ of simple $A$-modules $M$. The cocycle of $G_M$-action on $M^*$ is $\pi_M^1$. □

Theorem 2.4 gives a new interpretation of the Burnside ring $B^n_R(G)$. As a left $R$-module it is generated by $G$-Morita equivalence classes of semisimple split $G$-algebras subject to relations

$$[A \oplus B] = [A] + [B]$$

while the multiplication is given by the rule

$$[A] \cdot [B] = [A \odot B].$$

We finish this section outlining the role of generalised Burnside rings in number theory. A similar construction for the usual Burnside rings have recently been used by Dockchitsers to prove a partial case of the parity conjectures [7].

Let $\mathbb{F} \leq K$ be a $G$-Galois extension of algebraic number fields. Let us consider a central simple $n^2$-dimensional algebra $S$ over $K^H$, split over $K$, where $H$ is a subgroup of $G$. The algebra $S$ is uniquely determined up to an isomorphism by its system of factors $\alpha_S \in H^1(H, \text{PGL}_n(K))$. The long exact sequence in nonabelian cohomology gives an embedding $H^1(H, \text{PGL}_n(K)) \hookrightarrow H^2(H, K^\times)$. Thus, we can think that $\alpha_S \in H^2(H, K^\times)$. Then nonisomorphic algebras $S$ can have the same $\alpha_S$. By Artin-Wedderburn's theorem, $S \cong M_n(D_S)$ where $D_S$ is a simple central division algebra. Then $\alpha_S = \alpha_T$ if and only if $D_S \cong D_T$.

Now we can interpret $(a, H) \in B^n(G)$ as a Morita equivalence class $[A]$ of a simple $K^H$-algebra $A$ split over $K$ with $\alpha_A = a$. This class contains a unique (up to an isomorphism) division algebra $D$, so $(a, H) \in B^n(G)$ can also be interpreted as an isomorphism class $[D]$ of division $K^H$-algebras, split over $K$ with $\alpha_D = a$.

Now the extended Burnside ring will play the same role for the study of central simple algebras as the usual Burnside ring plays for the study of fields: various number theoretic concepts become group homomorphisms from $B^n(G)$ to abelian groups [7]. For instance, a zeta function $\zeta_D(z)$ of a division algebra $D$ extends to a group homomorphism to the meromorphic functions $\zeta: B^n(D) \rightarrow \mathbb{M}(z)$ on basis elements $\zeta((a, H)) = \zeta_D(z)$ where $D$ is the division central $K^H$-algebra, split over $K$ with $\alpha_D = a$.

3. Groupoids and $\mu_K$-decorated sets

Over a field $K$, there is a bijection between elements of $\mu_K(G)$ and isomorphism classes of central extensions

$$1 \rightarrow K^\times \rightarrow \tilde{G} \rightarrow G \rightarrow 1.$$  

The goal of this section is to observe that $\mu_K$-decorated sets admit a similar interpretation via groupoids. Any $G$-set $X$ defines the action groupoid $\mathcal{G}_X = G \times X$ over the base $X$. The maps $\pi_1, \pi_2 : \mathcal{G}_X \rightarrow X$ are $\pi_1(g, x) = g \cdot x$ and $\pi_2(g, x) = x$. The product $(g, x)(h, y) = (gh, y)$ is defined whenever $\pi_2(g, x) = \pi_1(h, y)$. A central extension of $\mathcal{G}_X$ by $K^\times$ is an exact sequence of groupoids

$$1 \rightarrow K^\times \times \Delta_X \rightarrow \tilde{G}_X \rightarrow \mathcal{G}_X \rightarrow 1$$

where $K^\times \times \Delta_X$ is a trivial groupoid on the diagonal $\Delta_X \subseteq X \times X$ [15], i.e., $\pi_1, \pi_2 : K^\times \times \Delta_X \rightarrow \Delta_X$ are both $\pi_1(y, x, x) = \pi_2(g, x, x) = (x, x)$ and $(g, x)(h, x, x) = (gh, x, x)$.

Lemma 3.1. There are natural bijections between the following sets:

1) isomorphism classes of finite $\mu_K$-decorated $G$-sets,
2) isomorphism classes of central extensions by $K^\times$ of $G$-action groupoids on finite sets.

Proof. Such central extensions are defined by central extensions of the diagonal groups $\mathcal{G}_{g,x} = \pi_1^{-1}(x) \cap \pi_2^{-1}(x)$. These diagonal groups are point stabilisers $G_x$ and their extensions are defined by $\pi_x \in \mu_K(G_x)$.

The equivariance assumption on frills is necessary for the existence of the central extension: each $g \in G$ defines an automorphism of $\tilde{G}$ by $(h, x) \mapsto (ghg^{-1}, gx)$. This automorphism gives an isomorphism between central extensions of $G_x$ and $G_{g,x}$. We leave it to the reader to check that the equivariance is sufficient for $\tilde{G}$ to be well defined.

Thus, central extensions of action groupoids and $\mu_K$-decorated sets are defined by the same data, so there is an obvious natural isomorphism between the sets of isomorphism classes of both. □

Furthermore, it is possible to characterise $B^n(G)$ in the language of central extension groupoids. We leave details to an interested reader.
4. Module categories and $\mu_K$-decorated sets

To explain the final (in this paper) interpretation of the generalised Burnside ring $\mathbb{B}^\mu(G)$, we need to contemplate the relation between a $G$-algebra $A$ and the semidirect product $A \ast G$. We have already seen that $A - \text{Mod}$ is a $G$-category. What is about $A \ast G - \text{Mod}$? It is a (right) module category over $G - \text{Mod}$. This means there is an exact tensor product bifunctor

$$\otimes : A \ast G - \text{Mod} \times G - \text{Mod} \to A \ast G - \text{Mod}$$

with associativity and unity natural transformations

$$(M \otimes V) \otimes V' \xrightarrow{\cong} M \otimes (V \otimes V'), \quad M \otimes K \xrightarrow{\cong} M$$

where $K$ is the trivial $G$-module subject to the commutativity of the pentagon and triangle diagrams [8, 16]. Both citations are comprehensive sources on module categories. We will use their terminology and results freely in this section.

The tensor product $M \otimes V$ of an $A \ast G$-module $M$ and a $G$-module $V$ is just the usual tensor product $M \otimes V$ of $G$-modules with $A$ acting on the first component. In fact, $A \ast G - \text{Mod}$ is naturally equivalent (as a module category) to the module category $A - \text{Mod}_G$ [8, 16]. To construct the latter, $A$ is considered as an algebra in $G - \text{Mod}$ and $A - \text{Mod}_G$ is the category of $A$-modules in $G - \text{Mod}$.

Now we indulge in a philosophical digression: the precise relation between $A - \text{Mod}$ and $A \ast G - \text{Mod}$ is of duality. Lemma 2.1 gives an equivalence between $A \ast G - \text{Mod}$ and the category of equivariant objects in $A - \text{Mod}$ with fixed equivariant structures. The Cohen-Montgomery duality for actions tells us that $(A \ast G)\#(\mathbb{B}^\mu G)^n \cong M_n(A)$ where $n$ is the order of $G$ [5]. Thus, $A - \text{Mod}$ is equivalent to $(A \ast G)\#(\mathbb{B}^\mu G)^n - \text{Mod}$ which is the category of $G$-graded $A \ast G$-modules. The duality assertion is further substantiated in Lemma 4.2.

**Lemma 4.1.** Let $A$ and $B$ be associative $G$-algebras. The categories $A \ast G - \text{Mod}$ and $B \ast G - \text{Mod}$ are equivalent as module categories over $G - \text{Mod}$ if and only if there exists a nondegenerate $G$-equivariant Morita context $(A, B, \lambda M_B, \nu N_A, \phi, \psi)$.

**Proof.** The category $A \ast G - \text{Mod}$ is naturally equivalent to $A - \text{Mod}_G$, the category of $A$-modules in $G - \text{Mod}$. A nondegenerate $G$-equivariant Morita context is just a nondegenerate Morita context in $G - \text{Mod}$. Thus, the lemma is just a standard Morita theorem stated inside the category $G - \text{Mod}$, for instance, our proof of Theorem 2.3 set in $G - \text{Mod}$ instead of vector space but with the trivial group will do the job.

It is useful to introduce intuitive geometric language [3, 1]. We can think of a $\mu_K$-decorated $G$-set $X$ as a $G$-Morita equivalence class $[A]$ of split semisimple $G$-algebras over $K$. By Lemma 4.1, the category $A \ast G - \text{Mod}$ is canonically attached to $X$. We call it the category of $G$-equivariant coherent sheaves on $X$ and denote $\text{Coh}_G(X)$. The rank of the Grothendieck group $K(A \ast G - \text{Mod})$, equal to the number of irreducible objects in $A \ast G - \text{Mod}$, can be thought of as an equivariant Euler characteristic $\mathfrak{M}(X)$ of the $\mu_K$-decorated $G$-set. This linearly extends to a function $\mathfrak{M} : \mathbb{B}^\mu G \to \mathbb{Z}$, whose values are appended to the tables.

Some of the considerations can be repeated if $G$ is no longer finite but an algebraic group acting on a finite set $X$. As the stabilisers of points are open, the finite component group $G/G_0$ acts on $X$, and one can understand a $\mu_K$-decorated $G/G_0$-set by a $\mu_K$-decorated $G$-set. Now the category $A \ast G - \text{Mod}$ consists only of those $A \ast G$-modules that are rational as $G$-modules. Now Lemma 4.1 can be repeated in $G$-modules and the category $\text{Coh}_G(X)$ is canonically attached to $X$.

A point $x = [N] \in X$ gives rise to a minimal central idempotents $e_x \in A$ such that $e_x N = N$. Using it, we define a stalk $M_x := e_x M$ and the support $\{ x \in X \mid e_x M \neq 0 \}$ of a sheaf $M$. This will be used in the next section.

Now we would like to discuss the relation of $\text{Coh}_G(X)$ to the module categories $H - \text{Mod}_\eta$. If $\eta \in \mu_K(H)$ and $H$ is a subgroup of $G$, the category $H - \text{Mod}_\eta$ is the category of projective representations of $H$, affording the cocycle $\eta$ [8, 16].

**Lemma 4.2.** Let $X$ be a finite $\mu_K$-decorated $G$-set, $X_0 \subseteq X$ a set of representatives of $G$-orbits. Then the category $\text{Coh}_G(X)$ is equivalent to $\oplus_{x \in X_0} G_x - \text{Mod}_{\mu_x}$ as a module category.
Proof. The functor $\Phi : \oplus_{x \in X_0} G_x - \text{Mod}_{\pi_x^{-1}} \to \text{Coh}_G(X)$ is constructed in two steps. First, we can associate a conjugate projective representation $V_x \in G_x - \text{Mod}_{\pi_x^{-1}}$, $x \in X$ to a formal sum $\oplus_{x \in X_0} V_x$. It is done exactly as in the proof of Theorem 2.4. Now let $M_x$ be the simple $A$-module that corresponds to the point $x \in X$. We define

$$\Psi(\oplus_{x \in X_0} V_x) = \oplus_{x \in X} M_x \otimes_{\mathsf{K}} V_x$$

with $A$ acting on the first components. $G_x$ acting on the tensor product $M_x \otimes_{\mathsf{K}} V_x$ (N.B., the cocycles cancel, so $H_x$ acts linearly) and elements of the transversal $T_x$ permuting the components in the orbit.

Its quasiinverse functor $\Psi : \text{Coh}_G(X) \to \oplus_{x \in X_0} G_x - \text{Mod}_{\pi_x^{-1}}$ is based on the canonical decomposition

$$L = \oplus_{x \in X} M_x \otimes \text{Hom}_A(M_x, L)$$

of an $A * G$-module $L$ (N.B., $A$ is semisimple). Observe that $L$ is a linear representation of $G$, $M_x$ a projective representation of $G_x$ with the cocycle $\pi_x$, so $\text{Hom}_A(M_x, L)$ is a projective representation of $G_x$ with the cocycle $\pi_x^{-1}$. Thus,

$$\Psi(L) = \oplus_{x \in X_0} \text{Hom}_A(M_x, L)$$

is the quasi-inverse functor. All the verifications are straightforward. \(\square\)

It is interesting that Lemma 4.2 holds without any assumption on characteristic $p$ of the field $\mathsf{K}$. If $p$ does not divide $|G|$ then every indecomposable semisimple module category over $G - \text{Mod}$ is equivalent to $H - \text{Mod}_\eta$ for some $H$, $\eta$ [16, Th 3.2]. Thus, $\text{Coh}_G(X)$ are all possible semisimple module categories.

Now if $p$ no longer divides $|G|$ then $A * G$ is not necessarily semisimple. However, it is relatively semisimple over $G - \text{Mod}$. It would be interesting whether $\text{Coh}_G(X)$ constitute all possible relatively semisimple module categories in this case. We avoid this difficulty by declaring a module category special if it is equivalent to a direct sum of $H - \text{Mod}_\eta$ as a module category.

**Theorem 4.3.** For a finite group $G$ there are natural bijections between the following sets:

1. isomorphism classes of finite $\mathbb{K}$-decorated $G$-sets,
2. isomorphism classes of central extensions by $\mathbb{K}^\times$ of $G$-action groupoids of finite sets,
3. $G$-Morita equivalence classes of semisimple split $G$-algebras,
4. equivalence classes of special module categories over $G - \text{Mod}$.

Proof. After Theorem 2.4 and Lemmas 3.1, 4.1 and 4.2, the only thing left to proof is that if $H - \text{Mod}_\eta$ is equivalent to $H' - \text{Mod}_\eta'$ as a module category then $(H, \eta)$ is conjugate to $(H', \eta')$. Let $X = G/H$, $X = G/H'$ with frills $\pi_H = g^{-1}y^{-1}$, $\pi_{H'} = g^{-1}y^{-1}$. Since $H - \text{Mod}_\eta$ is equivalent to $\text{Coh}_G(X)$, $\text{Coh}_G(X)$ is equivalent to $\text{Coh}_G(X')$. So $X$ must be isomorphic to $X'$ as decorated sets. If $\varphi : X' \to X$ is an isomorphism and $\varphi(H') = g$ then $g(H, \eta)q^{-1} = (H', \eta')$. \(\square\)

Using Theorem 4.3, one can interpret $\mathcal{B}^\mu(G)$ in the language of module categories. Let $[\mathcal{M}] \in \mathcal{B}^\mu(G)$ be the class of a special module category $\mathcal{M}$. Observe that if $\mathcal{M}$ and $\mathcal{N}$ are special module categories as in Theorem 4.3 then the category of module functors $\text{Fun}(\mathcal{M}, \mathcal{N})$ is a special module category and

$$[\text{Fun}(\mathcal{M}, \mathcal{N})] = [\mathcal{M}]^\vee \cdot [\mathcal{N}].$$

The remaining sections of the paper are devoted to applications of Burnside rings. An interesting group for the applications is the component group $A_\chi$ of a centraliser of a nilpotent element (in a simple Lie algebra) [3, 1]. The groups that occur as $A_\chi$ are symmetric groups $S_3$, $S_4$, $S_5$ and elementary abelian 2-groups $C_2^3$. A feature of these groups is that the Schur multipliers $\mu(A)$ of their subgroups are elementary abelian 2-groups. This implies that the involution $[X] \mapsto [X]^\vee$ is always trivial simplifying the calculations.

For instance, the number of simple objects in the module category $\text{Fun}(\mathcal{M}, \mathcal{N})$ over $A_\chi - \text{Mod}$ is $\mathfrak{M}([\mathcal{M}][\mathcal{N}])$. In the course of a proof [1, Th. 3], the authors show that for $[\mathcal{M}], [\mathcal{N}] \in \mathcal{B}^\mu(S_4)$ such that $\mathfrak{M}([\mathcal{M}][\mathcal{N}]) = \mathfrak{M}([\mathcal{N}][\mathcal{M}]) = 5$ and $\mathfrak{M}([\mathcal{M}][\mathcal{N}]) = 3$, either $[\mathcal{M}][\mathcal{N}] = \langle S_4 \rangle$ or $[\mathcal{N}][\mathcal{M}] = \langle S_4 \rangle$. This follows immediately from Table 1 since $\mathfrak{M}([\mathcal{M}][\mathcal{N}]) = 5$ implies $[\mathcal{M}] \in \{ \langle S_3 \rangle, \langle S_4 \rangle, \langle S_2 \rangle \}$.  

9
A Coxeter group $W$ admits three equivalence relations $\sim_L$, $\sim_R$ and $\sim_{LR}$. Equivalence classes of these relations are called left cells, right cells, and double cells correspondingly [13]. The definition of $\sim_L$ involves chains of elements, whose lengths may grow. Although no explicit bound on the lengths of elements is known, it is expected that $x \sim_L y$ can be decided by an efficient algorithm (cf., Casselman’s Conjecture [4]).

If $W$ is an affine Weyl group of a simple algebraic group $G^\vee$, cells admit a particularly revealing description. To a double cell $C \subseteq W$ Lusztig’ bijection associates a particular nilpotent coadjoint orbit $G \cdot \chi$ of the Langlands dual group $G$ (over $\mathbb{C}$ or any algebraically closed field of good characteristic). Let $G_\chi$ be the reductive part of the stabiliser of $\chi$, $\chi_\chi = G_\chi/G_{\chi, \chi}$ its component group. By Bezrukavnikov-Ostrik’s theorem, the cell admits a based $\mu$-decorated $A_\chi$-set $Y_C$ [3].

We refer an interested reader to the original Lusztig’s paper [13] for a full definition of the based set but one should be warned the sets there are not decorated. Here we list some of its properties, crucial for the further exposition here:

1. the permutation representation $\mathfrak{C}Y_C$ is isomorphic to the representation of $A_\chi$ on $H^*(B^\chi, \mathbb{C})$, the total cohomology of the Springer fibre,
2. there is a bijection between $C$ and the set of isomorphism classes of irreducible objects in $\text{Coh}_{G^\vee}(Y_C \times Y_C)$.
3. if $Y_C = \prod Y_i$, where $Y_i$ are $A_\chi$-orbits then the left cells correspond to sheaves supported on various $Y_C \times Y_i$ while the right cells correspond to sheaves on $Y_i \times Y_C$.

This information allows us to determine $Y_C$ uniquely if $A_\chi$ is cyclic. In particular, all Schur multipliers vanish in this case and all the decorations on the set $Y_C$ must be trivial. If $A_\chi = S_4$ then it is not clear how to determine $Y_C$ explicitly but the decorations must be trivial as all Schur multipliers vanish. The remaining component possible decoration groups are $S_4$, $S_3$ and elementary abelian 2-groups. The aim of this section is to compute $Y_C$ in the case of $A_\chi = S_4$.

This component group appears only in the type $F_4$ in the orbit $F_4(a_3)$. The corresponding double cell is

$$C = \{ x \in W \mid x \sim_{LR} s_2 s_3 s_2 s_3 \} = \{ x \in W \mid a(x) = 4 \}$$

where $W$ is the affine Weyl group of the type $F_4$, $a$ is Lusztig’s $a$-function, $s_2$, $s_3$ are the two simple reflections connected by the double arrow. The Green function [17] of $F_4(a_3)$ is

$$(\chi_{12} q^4 + (\chi_{8,3} + \chi_{8,1}) q^3 + \chi_{9,1} q^2 + \chi_{4,1} q + 1) \Sigma_{4} + (\chi_{9,3} q^4 + \chi_{8,3} q^3 + \chi_{2,3} q^2) \Sigma_{3,1} + (\chi_{6,2} q^4 + \chi_{4,1} q^3) \Sigma_{2,2} + \chi_{1,3} q^3 \Sigma_{3,1},$$

where $\Sigma_{\pi}$ denotes the irreducible character of $S_4$ corresponding to a partition $\pi$, $\chi_{n,m}$ is an irreducible $n$-dimensional character of the finite Weyl group $W_0$ of degree $m$. $q^k$ signifies that this component appears in degree $2k$ cohomology. Essentially, the Green function records $H^*(B^\chi, \mathbb{C})$ as a graded $A_\chi \times W_0$-module.

Let $\Omega : 3B(S_4) \to \text{Rep}(S_4)$ be the natural homomorphism that assigns its permutation representation to an $S_4$-set. Let $3B_+(S_4)$ be the effective part of the Burnside ring, i.e., the elements $[X]$ for actual $S_4$-sets. The following lemma is checked by a straightforward calculation and left to the reader.

**Lemma 5.1.** The equation

$$\Omega([X]) = 42 \Sigma_4 + 19 \Sigma_{3,1} + 10 \Sigma_{2,2} + \Sigma_{3,1}$$

has 20 solutions in $3B_+(S_4)$:

- $Y_\varepsilon = (15 + \varepsilon)(S_4) + (17 - \varepsilon)(S_3) + (9 - \varepsilon)(D_8) + (C_2) + \varepsilon(K_1),$
- $X_\varepsilon = (13 + \varepsilon)(S_4) + (19 - \varepsilon)(S_3) + (9 - \varepsilon)(D_8) + (C_4) + \varepsilon(K_1)$

for various $0 \leq \varepsilon \leq 9$.

These are 20 candidates for the base set $Y_C$. Points in the orbits with stabilisers $S_4$, $D_8$ and $K_1$ may have non-trivial decorations, so the total number of candidate $\mu$-decorated sets is much bigger. To advance our further knowledge we need to know some explicit information about the cell itself. More precisely, we need to know some elements in the 42 left cells contained in $C$. At present, no publicly available software can compute cells. However, we have managed to verify the following facts (stated as a proposition) on a computer.

**Proposition 5.2.** The following facts about the double cell $C = \{ x \in W(F_4) \mid a(x) = 4 \}$ are true:
(1) all left cells in C contain at least 151 elements,
(2) at least 30 cells in C contain at least 175 elements,
(3) the double cell C contains at least 7400 elements.

Proposition 5.2 can be verified on a computer by other research groups if they wish. Hopefully, it could be done using some standard packages in future. It allows us to pinpoint the base set of C further.

**Theorem 5.3.** If Proposition 5.2 holds, then the base set $Y_C$ is one of the 8 sets listed in upper half of Table 3.

**Proof.** Let $\overline{Y_C}$ be the underlying set of the decorated set $Y_C$. It must be one of the twenty sets listed in Lemma 5.1.

Using (1) of Proposition 5.2, we can rule out the case of $|\overline{Y_C}| = X_2$ because one the left cells will contain
$$2M([\overline{Y_C}] \cdot (C_4)) = 2M(X_2 \cdot (C_4)) = 2M(24(C_4) + 9(H_2) + 20(1)) = 24 \times 4 + 9 \times 2 + 20 = 134 < 151$$
Hence, $|\overline{Y_C}| = Y_2$ with $0 \leq \varepsilon \leq 9$.

Notice that $2M([\overline{Y_C}] \cdot (C_4)) = 2M(Y_2 \cdot (C_2)) = 2M(60(H_2) + 31(1)) = 60 \times 2 + 31 = 151$, so one of the left cells contains exactly 151 elements. Moreover, $(17 - \varepsilon)$ further left cells contain exactly $2M([\overline{Y_C}] \cdot (S_3)) = 2M(Y_2 \cdot (S_4)) = 2M(32(S_4) + 28(C_2) + 1) = 32 \times 3 + 28 \times 2 + 1 = 153$. By (2) of Proposition 5.2, at most 12 left cells may have such a small number of elements. So, $12 \geq 18 - \varepsilon$ and $9 \geq \varepsilon \geq 6$.

To pinpoint extensions, we introduce 3 more variables to write
$$Y_C = (15 + \varepsilon - \alpha)(S_4) + \alpha (S_4^\prime) + (17 - \varepsilon)(S_4) + (9 - \varepsilon - \beta)(D_8) + \beta(D_8^\prime) + (C_2) + (\varepsilon - \delta)(K_1) + \delta(K_1^\prime).$$
Since $Y_C = Y_C$, the number of elements in C is
$$2M(Y_C \cdot X_C) = 4e^2 - 4\varepsilon\alpha - 12\gamma + 30\rho + 6\varepsilon^2 + 12\alpha\beta + 12\alpha\gamma - 114\varepsilon + 12\delta^2 + 12\beta\gamma - 198\beta + 12\gamma^2 - 144\gamma + 7084.$$
Using Matlab, we find 14 possible extended sets that could give at least 7400 elements in the double cell. Results are summarised in table 3. The 6 sets in the lower half of the table contain a cell with less than 151 elements, thus contradicting (1).

Observe that the candidate sets come naturally in pairs, for instance, $[X] = 21(S_4) + 11(S_4) + 3(D_8) + (C_2) + 6(K_1)$ and $[Y] = 21(S_4^\prime) + 11(S_4^\prime) + 3(D_8^\prime) + (C_2) + 6(K_1^\prime)$. In each pair $X \times X^\vee \cong Y \times Y^\vee$, naturally. Thus, if one set in a pair is a base set, so is the second set. Since each pair contains a set with trivial decorations, we have established (subject to computer use in Proposition 5.2).

**Corollary 5.4.** The cell C admits an undecorated base set.

Our computer calculation establishes that certain elements are related by one of Kazhdan-Lusztig equivalences. At present, we do not know that the calculation completes all elements in the cell. However, the calculation indicates strongly that there are 11 cells of 153 elements. Thus, we can conclude (with a high degree of confidence but not definite) that the base sets of the cell C are
$$\langle X \rangle = 21(S_4) + 11(S_4) + 3(D_8) + (C_2) + 6(K_1)$$
and $\langle Y \rangle = 21(S_4^\prime) + 11(S_4^\prime) + 3(D_8^\prime) + (C_2) + 6(K_1^\prime)$.

6. Application: reduced enveloping algebras

Let $G$ be a simple simply-connected algebraic group over an algebraically closed field $\mathbb{K}$ of characteristic $p$ which is larger than the Coxeter number of $G$. Let $g$ be its Lie algebra, $\chi \in g^*$ a nilpotent element, $U = U_q(g)$ the reduced enveloping algebra. The finite dimensional algebra $U$ splits into blocks $U = \oplus \Lambda U^\Lambda$ that are parametrised by the orbits of the dual extended affine Weyl group $W^\Lambda = W_0 \rtimes \Lambda$ on the weight lattice $\Lambda$ via $(w, \mu) \cdot \lambda = w(\lambda + p\mu) - \rho$ where $\rho$ is the half-sum of simple roots [11]. The reductive part of the stabiliser $G_\chi$ acts on each $U^\Lambda$ [2]. We are interested in determining the $\mu$-decorated $G_\chi$-set $Y^\Lambda = \text{Irr}(U^\Lambda)$ for each $\Lambda$. As before, only the component group $A_\chi = G_\chi/G_\chi^0$ acts on $Y^\Lambda$, so it is a $\mu$-decorated $A_\chi$-set.

With our restriction on $p$, one can associate a parabolic subgroup $P = P(\lambda)$ (unique up to its type) to the weight $\lambda$ so that $\lambda$ is $P$-regular and $P$-unramified [2]. Let $W(\lambda)$ be the corresponding parabolic subgroup in the finite Weyl group $W_0$. Let $\Omega(Y^\Lambda)$ be the permutation representation of $A_\chi$ over $\mathbb{C}$. Then [2, 9],
$$\Omega(Y^\Lambda) \cong H^*(G/P, \mathbb{C}) \cong H^*(B^X, \mathbb{C})^{W(\lambda)}.$$ 
In particular, $\Omega(Y^\Lambda)$ depends only on the type of the parabolic. A stronger statement is true, which we formulate as a hypothesis.
Hypothesis. (1) $Y^\lambda$ depends only on the type of the parabolic.
(2) If $P(\nu) \subseteq P(\lambda)$ then there exists an $A_\lambda$-subset $Y_0^\lambda \subseteq Y^\lambda$ and a surjective morphism $Y_0^\lambda \to Y^\nu$ of $A_\lambda$-sets.

Both of these statements require the theory of translation functors. Statement (1) is well known [2, 11]. Statement (2) is not known and we are happy to leave it as a conjecture at this point. It needs a degeneration to a wall argument which is rather long and too specialised for this paper. It will be explained elsewhere.

Now we specialise the set-up to $g$ of the type $F_4$ and $\chi$ of the type $F_4(a_3)$, i.e., $\chi$ belongs to the only orbit with the component group $S_4$. It corresponds to the cell $C$ of the previous section under Lusztig’s bijection. The underlying undecorated $S_4$-sets of the sets $Y^\lambda$ are listed in Table 4. The left column contains the list of the types of parabolic subalgebras. The middle column describes the representation $\Omega(Y^\lambda)$ of $S_4$ by listing the multiplicities of irreducible constituents.

Now the right column describes the sets. The first five most degenerate parabolic types can be computed uniquely without the use of the hypothesis. Indeed,

$$\Omega(S_3) = \Sigma_4 + \Sigma_{3,1}$$

are the only permutation characters of $S_4$ that have only $\Sigma_4$ and $\Sigma_{3,1}$ as constituents.

The second two types can be computed using the hypothesis. Besides $\langle S_3 \rangle$ and $\langle S_4 \rangle$ there are four $S_4$-sets without $\Sigma_{1,1,1,1}$ in the permutation representation:

$$\Omega(C_2) = \Sigma_4$$
$$\Omega(C_4) = \Sigma_4 + 2\Sigma_{3,1} + \Sigma_{2,2} + \Sigma_{2,1,1}$$

The $S_4$-set for $W(1,2)$ can be degenerated to the sets for $W(1,3,4)$, hence it is at least $3\langle S_4 \rangle + 4\langle S_3 \rangle$. The rest of the set has the permutation character $4\Sigma_4 + 5\Sigma_{3,1} + \Sigma_{2,2} + \Sigma_{2,1,1}$ leaving the only possibility of $\langle C_2 \rangle + 3\langle S_3 \rangle$. Similarly, the set for $W(3,4)$ degenerates to the set for $W(1,3,4)$, so it is at least $6\langle S_4 \rangle + \langle S_3 \rangle$, leaving the only possibility of $9\langle S_4 \rangle + \langle S_3 \rangle$.

The remaining five sets cannot be uniquely determined by this method. One needs to know how many times $\langle K_1 \rangle$ appears in the set. We make this multiplicity into a parameter and list the remaining sets. We expect all the frills on all $Y^\lambda$ to be trivial and $e = 6$ in the light of the following Lusztig’s conjecture [14]:

Conjecture. For each $G$ and $\chi$
(1) the frills of $Y^\lambda$ are trivial,
(2) $Y^0$ is a base set of the double cell in the dual affine Weyl group of $G$ that corresponds to the orbit of $\chi$ under Lusztig’s bijection.

References

### 7. Appendix: Tables

#### Table 1. The extended table of marks of $S_4$.

<table>
<thead>
<tr>
<th>$\mathbb{M}$</th>
<th>$\mathbb{N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1$</td>
<td>$24$</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$12$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$C_3$</td>
<td>$8$</td>
</tr>
<tr>
<td>$C_4$</td>
<td>$6$</td>
</tr>
<tr>
<td>$S_4$</td>
<td>$4$</td>
</tr>
<tr>
<td>$K_1$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_2$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_3$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_4$</td>
<td>$6$</td>
</tr>
<tr>
<td>$D_3$</td>
<td>$3$</td>
</tr>
<tr>
<td>$A_4$</td>
<td>$2$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

#### Table 2. The extended table of marks of $S_5$.

<table>
<thead>
<tr>
<th>$\mathbb{M}$</th>
<th>$\mathbb{N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1$</td>
<td>$120$</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$60$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>$60$</td>
</tr>
<tr>
<td>$C_3$</td>
<td>$40$</td>
</tr>
<tr>
<td>$C_4$</td>
<td>$30$</td>
</tr>
<tr>
<td>$C_5$</td>
<td>$24$</td>
</tr>
<tr>
<td>$S_5$</td>
<td>$20$</td>
</tr>
<tr>
<td>$H_6$</td>
<td>$12$</td>
</tr>
<tr>
<td>$C_3 \times C_2$</td>
<td>$20$</td>
</tr>
<tr>
<td>$D_10$</td>
<td>$12$</td>
</tr>
<tr>
<td>$K_1$</td>
<td>$20$</td>
</tr>
<tr>
<td>$K_2$</td>
<td>$20$</td>
</tr>
<tr>
<td>$K_3$</td>
<td>$20$</td>
</tr>
<tr>
<td>$K_4$</td>
<td>$20$</td>
</tr>
<tr>
<td>$K_5$</td>
<td>$20$</td>
</tr>
<tr>
<td>$D_5$</td>
<td>$15$</td>
</tr>
<tr>
<td>$S_4$</td>
<td>$10$</td>
</tr>
<tr>
<td>$H_6$</td>
<td>$6$</td>
</tr>
<tr>
<td>$C_3 \times C_2$</td>
<td>$10$</td>
</tr>
<tr>
<td>$D_10$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_1$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_2$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_3$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_4$</td>
<td>$6$</td>
</tr>
<tr>
<td>$K_5$</td>
<td>$6$</td>
</tr>
<tr>
<td>$D_5$</td>
<td>$5$</td>
</tr>
<tr>
<td>$S_4$</td>
<td>$5$</td>
</tr>
<tr>
<td>$H_6$</td>
<td>$5$</td>
</tr>
<tr>
<td>$C_3 \times C_2$</td>
<td>$5$</td>
</tr>
</tbody>
</table>

---

Department of Mathematics and Statistics, University of Massachusetts, Amherst, MA 01003, USA
E-mail address: gunnells@math.umass.edu

Mathematics Department, University of Warwick, Coventry, CV4 7AL, UK
E-mail address: a.j.rose@warwick.ac.uk

Department of Mathematics, University of Warwick, Coventry, CV4 7AL, UK
E-mail address: D.Rumynin@warwick.ac.uk
### Table 3. Candidate base $S_4$-sets for cell $F_4(a_3)$.  

<table>
<thead>
<tr>
<th>$a$</th>
<th>Set</th>
<th>double cell size</th>
<th>partition into left cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>$21(S_4) + 11(S_3) + 3(D_6) + (C_2) + 6(K_1)$</td>
<td>7408</td>
<td>(151, 153, 192, 193, 206)</td>
</tr>
<tr>
<td>7</td>
<td>$22(S_4) + 10(S_3) + (C_2) + 7(K_4)$</td>
<td>7408</td>
<td>(151, 153, 192, 193, 206)</td>
</tr>
<tr>
<td>8</td>
<td>$23(S_4) + 9(S_3) + (D_6) + (C_2) + 8(K_1)$</td>
<td>7560</td>
<td>(151, 153, 192, 193, 206)</td>
</tr>
<tr>
<td>9</td>
<td>$24(S_4) + 8(S_3) + (C_2) + 9(K_1)$</td>
<td>7678</td>
<td>(151, 153, 182, 215)</td>
</tr>
</tbody>
</table>

### Table 4. $S_4$-sets from parabolic blocks of $U_\chi$ with $\chi$ of type $F_4(a_3)$.  

<table>
<thead>
<tr>
<th>$a$</th>
<th>$\Sigma_{1,1}$</th>
<th>$\Sigma_{2,2}$</th>
<th>$\Sigma_{2,1,1}$</th>
<th>$\Sigma_{1,1,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W(1, 2, 3)$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W(1, 2, 3)$</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W(1, 2, 4)$</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W(2, 3, 4)$</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W(1, 3, 4)$</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W(1, 2, 3, 4)$</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

| $W(1, 3)$ | 16 | 6 | 2 | 0 | $(1 + \alpha)(S_4) + (9 - \alpha)(S_3) + (2 - \alpha)(D_6) + \alpha(K_1)$, $\alpha \leq 2$ |
| $W(2, 3)$ | 10 | 4 | 2 | 0 | $4 + \beta)(S_4) + (4 - \beta)(S_3) + (2 - \beta)(D_6) + \beta(K_1)$, $\beta \leq 2$ |
| $W(1)$ | 25 | 14 | 5 | 1 | $(8 + \gamma)(S_4) + (12 - \gamma)(S_3) + (4 - \gamma)(D_6) + (C_2) + \gamma(K_1)$, max$(\alpha, \beta) \leq \gamma \leq 2$ |
| $W(0)$ | 42 | 19 | 10 | 1 | $15 + \epsilon)(S_4) + (17 - \epsilon)(S_3) + (9 - \epsilon)(D_6) + (C_2) + \epsilon(K_1)$, max$(\gamma, \delta) \leq \epsilon \leq 8$ |