An integral second fundamental theorem of invariant theory for partition algebras

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April 11, 2018

Abstract

We prove that the kernel of the action of the group algebra of the Weyl group acting on tensor space (via restriction of the action from the general linear group) is a cell ideal with respect to the alternating Murphy basis. This provides an analogue of the second fundamental theory of invariant theory for the partition algebra over an arbitrary integral domain and proves that the centraliser algebras of the partition algebra are cellular. We also prove similar results for the half partition algebras.

Introduction

The partition algebra $\mathcal{P}_r(n)$ over the complex field $\mathbb{C}$ arose in work of Paul Martin [Mar91, Mar94] and (independently) Vaughan Jones [Jon94] as a generalisation of the Temperley–Lieb algebra for $n$-state $r$-site Potts models in statistical mechanics. Suppose that $V$ is an $n$-dimensional complex vector space. The algebra $\mathcal{P}_r(n)$ arises as the (generic) centraliser of the Weyl group $W_n$ of $\text{GL}(V)$ on tensor space $V^\otimes r$. By the general theory of finite dimensional algebras it follows that the $(\mathbb{C}W_n, \mathcal{P}_r(n))$-bimodule $V^\otimes r$ satisfies Schur–Weyl duality (see [HR05]), in the sense that the image of each representation coincides with the centraliser algebra of the other action.

The partition algebra has found surprising applications to Deligne’s tensor categories (see [Del07, COT11, CWT12, COT14]) and the study of the Kronecker coefficients (see [BDO15]). Heuristically speaking, this is because the partition algebra controls stability phenomena arising in the representation theory of symmetric groups.
More generally, let $V$ be a free $k$-module of rank $n$ over an arbitrary unital ring $k$. The partition algebra makes sense as an algebra over $k$, and $V^\otimes r$ is a $(kW_n, \mathcal{P}_r(n))$-bimodule. In a companion paper [BDM18], the authors have shown that Schur–Weyl duality holds over $k$. Therefore, it is natural to expect that the partition algebra will continue to influence stability phenomena of symmetric groups over fields of positive characteristic.

The main result of this paper, Theorem 7.5, is that for any integral domain $k$, the annihilator of the $kW_n$-action on $V^\otimes r$ is a cell ideal with respect to the alternating Murphy basis of $kW_n$. (The theory of cellular algebras was introduced in [GL96].) In light of Schur–Weyl duality, our main result implies (Corollary 7.6) that the centraliser algebra $\text{End}_{\mathcal{P}_r(n)}(V^\otimes r)$ inherits a cellular structure from that of $kW_n$ — even better, we obtain an explicit cellular basis. Thus our main result provides an analogue of the second fundamental theory of invariant theory for the partition algebra over an arbitrary integral domain $k$. Similar results for other diagram algebras have been obtained in [Här99, LZ12, BEG17].

One can ask for conditions under which a centraliser algebra of a cellular algebra is again cellular; this general question seems to be poorly understood at present. Our result establishes another positive occurrence of such a phenomenon. We note that it is not at present known whether or not the centraliser algebra $\text{End}_{W_n}(V^\otimes r)$ is always cellular, although explicit descriptions of the annihilator of the action of $\mathcal{P}_r(n)$ have been obtained in [HR05, BH17, BH17b].

Finally, we remark that Paul Martin [Mar00] introduced the half partition algebras $\mathcal{P}_{r+1/2}(n)$ in order to collate the individual (ordinary and half) partition algebras together in a tower of recollement structure. Our results treat both algebras $\text{End}_{\mathcal{P}_r(n)}(V^\otimes r)$ and $\text{End}_{\mathcal{P}_{r+1/2}(n)}(V^\otimes r)$ uniformly.

Acknowledgements. The authors thank the organisers of the conference “Representation theory of symmetric groups and related algebras” held at the Institute for Mathematical Sciences, National University of Singapore (December 2017), for providing an excellent venue for working on this paper.

1 Combinatorics of symmetric groups

We write $\text{Sym}_S$ for the symmetric group of permutations of a set $S$ (the bijections of $S$ under composition). We write $\text{Sym}_d$ for $\text{Sym}_{\{1, \ldots, d\}}$. For any set $S$ with $|S| = d$ we identify $\text{Sym}_S$ with $\text{Sym}_d$ via the obvious isomorphism.
A weak composition of a non-negative integer $d$ is a way of writing $d$ as the sum of a sequence of non-negative integers. There are infinitely many weak compositions of $d$, because we can always append 0 to any weak composition. Weak compositions are usually identified with infinite sequences with finite support (finitely many non-zero terms). The length of a weak composition $(\lambda_1, \lambda_2, \ldots)$ is the largest $\ell$ for which $\lambda_\ell \neq 0$, thus we write $\lambda$ as $\lambda = (\lambda_1, \ldots, \lambda_\ell)$. There are finitely many weak compositions with a specified upper bound on length.

A composition of $d$ is a way of writing $d$ as the sum of a sequence of (strictly) positive integers. So a composition is a weak composition with positive parts, and its length is the number of parts. We stipulate that the integer 0 has one composition, of length 0, defined by the empty sequence. We write $\lambda \vDash d$ to mean that $\lambda = (\lambda_1, \ldots, \lambda_\ell)$ is a composition of $d$.

Two sequences that differ in the order of their terms define different compositions of their sum, while they are considered to define the same partition of that number. Thus, partitions may be identified with ordered compositions. Typically the chosen ordering is the descending one. We write $\lambda \vdash d$ to mean that $\lambda$ is a partition of $d$.

Given a weak composition $\lambda = (\lambda_1, \ldots, \lambda_\ell)$ of $d$, a Young diagram of shape $\lambda$ is a planar arrangement of boxes into rows, with $\lambda_i$ boxes in the $i$th row, for each $i = 1, \ldots, \ell$. A $\lambda$-tableau $t$ is a numbering of the boxes by the numbers $1, \ldots, d$; i.e., a map from $\{1, \ldots, d\}$ to the boxes. A tableau is row standard if the numbers in each row are increasing when read from left to right, and standard if row standard and the numbers in each column are increasing when read from top to bottom.

If $H$ is a subgroup of a finite group $G$ and $V$ a left or right $kH$-module, where $k$ is a ring, we respectively have the left or right induced module

$$\text{ind}^G_H V = kG \otimes_{kH} V \text{ or } V \otimes_{kH} kG.$$ 

To each weak composition $\lambda = (\lambda_1, \ldots, \lambda_\ell)$ of $d$ there corresponds the following data:

(i) The row-reading tableau $t^\lambda$ of shape $\lambda$, in which the numbers $1, \ldots, d$ are written from left to right in the rows.

(ii) The Young subgroup $\text{Sym}_\lambda$ of $\text{Sym}_d$; this the subgroup of $\text{Sym}_d$ stabilising the rows of $t^\lambda$.

(iii) The permutation module $M^\lambda$, defined by

$$M^\lambda = \text{ind}^{\text{Sym}_d}_{\text{Sym}_\lambda} k.$$
It has a (tabloid) basis \([\text{Jam78}]\) indexed by the set of row-standard tableaux of shape \(\lambda\).

Permutation modules (both as left and right modules) play an important role in what follows. As a left \(k\)\(\text{Sym}_d\)-module, it is well known that \(M^\lambda\) is isomorphic to the left ideal \(k\)\(\text{Sym}_d x_\lambda\), where \(x_\lambda\) is defined in the next paragraph.

Given a row-standard \(\lambda\)-tableau \(t\), let \(d(t)\) be the unique element of \(\text{Sym}_d\) such that \(t = d(t)\lambda\). Let \(\text{sgn} \, w\) be the sign of a permutation \(w\). Given any pair \(s, t\) of row-standard \(\lambda\)-tableaux, following Murphy, we set

\[
(1) \quad x^\lambda_{st} = d(s)^{-1} x_\lambda d(t); \quad y^\lambda_{st} = d(s)^{-1} y_\lambda d(t).
\]

where \(x_\lambda = \sum_{w \in W_\lambda} w\) and \(y_\lambda = \sum_{w \in W_\lambda} (\text{sgn} \, w) \, w\). If \(\lambda\) is already specified in context, then we may omit the superscript \(\lambda\) from the notation, writing \(x_{st}, y_{st}\) instead of the more cumbersome \(x^\lambda_{st}, y^\lambda_{st}\).

Graham and Lehrer \([\text{GL96}]\) introduced cellular algebras in order to axiomatise certain common features of certain classes of finite dimensional algebras. A cellular algebra is an algebra with a distinguished basis (the cellular basis) indexed by triples \((\lambda, s, t)\) where \(\lambda\) varies over a poset. The basis yields canonical pairwise non-isomorphic cell modules \(\Delta(\lambda)\), one for each \(\lambda\) in the indexing set. For each \(\lambda, s\) and \(t\) belong to an index set in bijection with a basis of \(\Delta(\lambda)\).

Murphy \([\text{Mur92}, \text{Mur95}]\) found two cellular bases of the Iwahori–Hecke algebra associated to \(k\)\(\text{Sym}_d\). By specialising the deformation parameter to 1, we obtain cellular bases of \(k\)\(\text{Sym}_d\) as follows.

**Theorem 1.1** (Murphy). Let \(k\) be a commutative ring. Each of the two disjoint unions

\[
\mathcal{X} = \bigsqcup_{\lambda \vdash d} \{x_{st} \mid s, t \text{ standard}, [s] = [t] = \lambda\},
\]

\[
\mathcal{Y} = \bigsqcup_{\lambda \vdash d} \{y_{st} \mid s, t \text{ standard}, [s] = [t] = \lambda\}
\]

is a cellular \(k\)-basis of the group algebra \(k\)\(\text{Sym}_d\), with anti-involution \(*\) the \(k\)-linear map sending \(w\) to \(w^{-1}\), for any \(w \in \text{Sym}_d\). The cells are ordered by reverse dominance order \(\succeq\), with the least dominant partition \((1^n)\) at the top and the most dominant partition \((n)\) at the bottom. The cell module \(\Delta(\lambda)\) indexed by \(\lambda\) is isomorphic to the dual Specht module \(S_\lambda\) for the \(x\)-basis and the Specht module \(S^{\lambda^t}\) for the \(y\)-basis, where \(\lambda^t\) is the transpose of \(\lambda\).
Note that \( x_{st} \) and \( y_{st} \) are interchanged by the \( k \)-linear ring involution of \( k \text{Sym}_d \) defined by sending \( w \) to \((\text{sgn } w)w\), for \( w \in \text{Sym}_d \). This involution converts results about one basis into results about the other. Further details on Murphy’s results are available in [Dot07].

**Remark 1.2.** We need to distinguish notationally between two symmetric groups in this paper: \( W_n \cong \text{Sym}_n \) and \( \mathcal{S}_r \cong \text{Sym}_r \). We write maps on the left in the former, on the right in the latter. Thus, we compose from right-to-left in \( W_n \) and from left-to-right in \( \mathcal{S}_r \). These groups act on \( V^{\otimes r} \) on the left and right by value and place-permutation, respectively. Any notation applicable to \( \text{Sym}_n \) will be extended to both \( W_n \) and \( \mathcal{S}_r \); in particular we have the Young subgroups \( W_\lambda \) and \( \mathcal{S}_\mu \) for any weak compositions \( \lambda \), \( \mu \) of \( n \), \( r \) respectively.

## 2 The \((kW_n, \mathcal{P}_r(n))\)-bimodule \( V^{\otimes r} \)

For the rest of the paper we fix a free \( k \)-module \( V \) of rank \( n \), with a given \( k \)-basis \( \{v_1, \ldots, v_n\} \), where \( k \) is a unital ring. We identify \( V \) with \( k^n \) by taking coordinates in the basis. For any positive integer \( r \), the set

\[
\{ v_{i_1} \otimes \cdots \otimes v_{i_r} \mid i_1, \ldots, i_r = 1, \ldots, n \}
\]

is a basis of the \( r \)th tensor power \( V^{\otimes r} \). The general linear group \( \text{GL}(V) \) of \( k \)-linear automorphisms of \( V \) acts naturally on the left on \( V \); this action extends diagonally to an action on \( V^{\otimes r} \). The symmetric group \( \mathcal{S}_r \) acts on the right on \( V^{\otimes r} \) by permuting the tensor positions; this action is known as the place-permutation action, defined by

\[
(v_{i_1} \otimes \cdots \otimes v_{i_r})^\sigma = v_{i_{\sigma^{-1}}r} \otimes \cdots \otimes v_{i_{\sigma^{-1}}1} \quad \text{for } \sigma \in \mathcal{S}_r
\]

extended linearly. Note that we write maps in \( \mathcal{S}_r \) on the right of their arguments, so that we may compose permutations in \( \mathcal{S}_r \) from left-to-right. The actions of the groups \( \text{GL}(V) \), \( \mathcal{S}_r \) on \( V^{\otimes r} \) commute, thus their linear extensions to the group algebras makes \( V^{\otimes r} \) into a \((k \text{GL}(V), k\mathcal{S}_r)\)-bimodule.

Basis elements \( v_{i_1} \otimes \cdots \otimes v_{i_r} \) of \( V^{\otimes r} \) are indexed by multi-indices \( (i_1, \ldots, i_r) \) in the set

\[
I(n, r) = \{1, \ldots, n\}^r.
\]

In the sequel, we will be careful to distinguish between values \( i_\alpha \) in \( \{1, \ldots, n\} \) and places \( \alpha \) in \( \{1, \ldots, r\} \). For example, the multi-index \( (2, 7, 7, 6, 2) \) takes the value 7 in places 2, 3, the value 2 in places 1, 5, and the value 6 in place
4. In general, we will use Latin letters such as $i, j$ to denote values and Greek letters such as $\alpha, \beta$ to denote places.

Let $W_n$ be the Weyl group of $\text{GL}(V)$, i.e., the group of elements of $\text{GL}(V)$ permuting the basis $\{v_1, \ldots, v_n\}$. We identify $W_n$ with the group of permutation matrices, regarded as matrices with entries from $k$. By restricting the action of $\text{GL}(V)$ to $W_n$, we obtain a left action of $W_n$ on $V^\otimes r$. To be explicit, $w \in W_n$ acts by

$$w(v_{j_1} \otimes \cdots \otimes v_{j_r}) = v_{w(j_1)} \otimes \cdots \otimes v_{w(j_r)}.$$  

Note that we write maps on the left of their arguments when considering this action. Extended linearly, the action of $W_n$ defines a linear representation $kW_n \to \text{End}_k(V^\otimes r)$ of the group algebra $kW_n$.

Thus, we have actions of two symmetric groups, $W_n \cong \text{Sym}_n$ and $\mathfrak{S}_r \cong \text{Sym}_r$, one acting (on the left) on values and the other (on the right) on places. We distinguish these groups notationally throughout the paper because their roles are quite different.

For a positive integer $r$, and any $\delta \in k$, we let $\mathcal{P}_r(\delta)$ denote the $k$-module with basis given by all set-partitions of $\{1, 2, \ldots, r, 1', 2', \ldots, r'\}$. By a set-partition we mean a pairwise disjoint covering of the set. A subset of a set-partition is called a block. For example,

$$d = \{\{1, 2, 4, 2', 5\}, \{3\}, \{5, 6, 7, 3', 4', 6', 7'\}, \{8, 8'\}, \{1'\}\}$$

is a set-partition of the set $\{1, \ldots, 8, 1', \ldots, 8'\}$ with five blocks.

We can depict each set-partition by a partition diagram, consisting of $r$ northern nodes indexed by $1, 2, \ldots, r$ and $r$ southern nodes indexed by $1', 2', \ldots, r'$, with edges between nodes, such that the nodes in the connected components give the blocks of the set-partition. In general there are many partition diagrams depicting a given set-partition, the choice of which does not matter.

We define the product $x \cdot y$ of two diagrams $x$ and $y$ by stacking $x$ above $y$, where we identify the southern nodes of $x$ with the northern nodes of $y$; these identified nodes then become the middle nodes. If there are $m$ connected middle components, then the product $xy$ is set equal to $\delta^m$ times the diagram obtained by removing the middle components (including middle vertices). An example is given in Figure 1. Extending the product linearly defines a multiplication on $\mathcal{P}_r(\delta)$, making it an associative algebra. Note that $k\mathfrak{S}_r \subset \mathcal{P}_r(\delta)$ is the subalgebra spanned by the permutation diagrams, the diagrams depicting set-partitions with $r$ blocks, each of which contains exactly one element of $\{1, \ldots, r\}$ and one of $\{1', \ldots, r'\}$. 
Figure 1: Multiplication of two diagrams in $P_5(\delta)$.

To obtain an action of the partition algebra on $V \otimes r$, it is necessary to specialise $\delta$ to $n = \text{rank}_k V$. Following [HR05], we define a generalised Kronecker delta symbol $(d)_{i_1 \ldots i_r}$ corresponding to a diagram $d$ and any $(i_1, \ldots, i_r), (i'_1, \ldots, i'_r)$ in $I(n, r)$, by

$$(d)_{i_1 \ldots i_r} = \begin{cases} 1 & \text{if } i_\alpha = i_\beta \text{ whenever } \alpha \neq \beta \text{ are in the same block of } d \\ 0 & \text{otherwise.} \end{cases}$$

Then the diagram $d$ acts on $V \otimes r$, on the right, by the rule

$$(5) \quad (v_{i_1} \otimes \cdots \otimes v_{i_r})^d = \sum_{(i'_1, \ldots, i'_r) \in I(n,r)} (d)_{i_1' \ldots i_r'} (v_{i_1'} \otimes \cdots \otimes v_{i_r'}).$$

Extended linearly, this action defines a linear representation $P_r(n)^{\text{op}} \to \text{End}_k(V \otimes r)$. If $d \in \mathcal{G}$ is a permutation diagram, then $d$ acts by the place-permutation action defined in (3). The actions of $W_n$ and $P_r(n)$ defined in (4) and (5) commute, thus we have a $(k W_n, P_{r+1/2}(n))$-bimodule structure on $V \otimes r$.

3 The $(k W_{n-1}, P_{r+1/2}(n))$-bimodule $V \otimes r$

Let $P_{r+1/2}(\delta)$ denote the submodule of $P_{r+1}(\delta)$ with $k$-basis given by all set-partitions such that $r + 1$ and $(r + 1)'$ belong to the same block. The submodule $P_{r+1/2}(\delta)$ is closed under the multiplication and therefore is a subalgebra of $P_{r+1}(\delta)$. The $k$-submodule $V \otimes r \otimes v_n \subset V^{\otimes (r+1)}$ is stable under the action of $P_{r+1/2}(n)$. Therefore, by identifying $V \otimes r$ with $V \otimes r \otimes v_n \subset V^{\otimes (r+1)}$

we regard $V \otimes r$ as a right $P_{r+1/2}(n)$-module. We also regard it as a left $k W_{n-1}$-module by restriction from $k W_n$, where

$$W_{n-1} = \{ w \in W_n \mid w(n) = n \}.$$

Thus, after identifying $V \otimes r$ with $V \otimes r \otimes v_n$, we have a $(k W_{n-1}, P_{r+1/2}(n))$-bimodule structure on $V \otimes r$. 

7
4 Decompositions of $V^\otimes r$

Henceforth we study $V^\otimes r$ as left $kW_n$-module and also as left $kW_{n-1}$-module (subject to the identification of $V^\otimes r$ with $V^\otimes r \otimes v_n$, discussed in Section 3).

We write

$$\Phi_{n,r} : kW_n \to \text{End}_k(V^\otimes r), \quad \Phi_{n,r+1/2} : kW_{n-1} \to \text{End}_k(V^\otimes r)$$

for the $k$-linear representations corresponding to the left actions in the two bimodule structures on $V^\otimes r$. Our goal is to understand the annihilator of each action. In this section we obtain direct sum decompositions of $V^\otimes r$, as both left $kW_n$ and $kW_{n-1}$-modules, but first we record the following elementary fact.

**Lemma 4.1.** If $r \geq n$ then the representation $\Phi_{n,r} : kW_n \to \text{End}_k(V^\otimes r)$ is faithful. If $r + 1 \geq n$ then the representation $\Phi_{n,r+1/2} : kW_{n-1} \to \text{End}_k(V^\otimes r \otimes v_n)$ is faithful.

**Proof.** Suppose that $a = \sum_{w \in W_n} a_w w$ belongs to the kernel of $\Phi_{n,r}$. Then $a$ acts as zero on all elements of $V^\otimes r$. First suppose that $r = n$. Consider the simple tensor $v = v_1 \otimes v_2 \otimes \cdots \otimes v_n$. We have

$$w \cdot v = v_{w(1)} \otimes v_{w(2)} \otimes \cdots \otimes v_{w(n)}$$

and each $w \cdot v$ is a simple tensor obtained from $v$ by permuting its factors according to $w$. In particular, the set $\{w \cdot v \mid w \in W_n\}$ is linearly independent over $k$. Thus the fact that $a \cdot v = 0$ implies that

$$\sum_{w \in W_n} a_w (v_{w(1)} \otimes v_{w(2)} \otimes \cdots \otimes v_{w(n)}) = 0.$$ 

By linear independence, this forces $a_w = 0$ for all $w \in W_n$; that is, $a = 0$. This proves the first claim in case $r = n$.

For the general case, $r \geq n$, replace $v$ by $v \otimes v_n^\otimes (r-n)$ and repeat the argument. This proves the first claim. The proof of the second claim is similar. \hfill $\square$

**Remark 4.2.** Lemma 4.1 will be sharpened in Corollary 4.13. The preceding argument can be modified to prove the sharpened result; we leave the details to the interested reader.

Although not needed in this paper, for purposes of comparison we recall the standard multiplicity-free decomposition of $V^\otimes r$ as a right $k\mathfrak{S}_r$-module:

$$V^\otimes r \cong \bigoplus_\lambda M^\lambda$$

(6)
where the sum is over all weak compositions of \( r \) of length at most \( n \). To see this, observe that each \( M^\lambda \) may be identified with the weight space \( V_\lambda^{\otimes r} \) consisting of all tensors of weight \( \lambda \) for the action of the diagonal torus \( T \subset \text{GL}(V) \) (elements of \( \text{GL}(V) \) acting diagonally on the basis vectors \( v_i \)). The identification \( V_\lambda^{\otimes r} \cong M^\lambda \) is given on basis elements by

\[
(7) \quad v_{i_1} \otimes \cdots \otimes v_{i_r} \mapsto t(i_1, \ldots, i_r),
\]

where \( t(i_1, \ldots, i_r) \) is the row-standard \( \lambda \)-tableau whose \( j \)th row contains all the tensor places in which \( v_j \) appears.

Now we tackle the problem of decomposing \( V^{\otimes r} \), both as a left \( kW_n \) and \( kW_{n-1} \)-module. To that end, we make the following definitions.

**Definition 4.3.** The *value-type* of a multi-index \((i_1, \ldots, i_r)\) in \( I(n, r) \) is the set-partition \( \Lambda \) of \( \{1, \ldots, r\} \) defined by \( \Lambda = \{\Lambda_1, \ldots, \Lambda_n\} \), where \( \Lambda_j \) is the set of places \( \alpha = 1, \ldots, r \) such that \( i_\alpha = j \). By convention, we usually omit any empty subsets \( \Lambda_j \) from \( \Lambda \). The non-empty subsets in \( \Lambda \) are called *parts*; their number is denoted by \( \ell(\Lambda) \) and is called the *length* of \( \Lambda \).

The non-empty parts of the value-type \( \Lambda \) associated to \((i_1, \ldots, i_r)\) are the subsets given by the non-empty rows of the associated tableau \( t(i_1, \ldots, i_r) \) defined in (7). For instance, the value-type of the multi-index

\[
(i_1, \ldots, i_7) = (9, 8, 8, 1, 9, 8, 1)
\]
is \( \Lambda = \{\{1, 5\}, \{2, 3, 6\}, \{4, 7\}\} \), a set-partition of \( \{1, \ldots, 7\} \) with three parts.

**Definition 4.4.** Let \( \Lambda \) be a set-partition of \( \{1, \ldots, r\} \) with not more than \( n \) parts. We define \( V(\Lambda) \) to be the \( k \)-span of the tensors \( v_{i_1} \otimes \cdots \otimes v_{i_r} \) such that the value-type of \((i_1, \ldots, i_r)\) is equal to \( \Lambda \).

Similarly, for each set-partition \( \Lambda' \) of \( \{1, \ldots, r+1\} \) with not more than \( n \) parts, we define \( V'(\Lambda') \) to be the \( k \)-span of the tensors \( v_{i_1} \otimes \cdots \otimes v_{i_r} \otimes v_n \) such that the value-type of \((i_1, \ldots, i_r, n)\) is equal to \( \Lambda' \).

It is useful to understand how \( V'(\Lambda') \) is related to \( V(\Lambda') \). Of course we have \( V'(\Lambda') \subseteq V(\Lambda') \) by definition. To be more specific, we have the following result.

**Lemma 4.5.** For any set-partition \( \Lambda' \) of \( \{1, \ldots, r+1\} \) with not more than \( n \) parts, \( \text{rank}_k V'(\Lambda') = \frac{1}{n} \text{rank}_k V(\Lambda') \).
Proof. Let \( v = v_{i_1} \otimes \cdots \otimes v_{i_r} \otimes v_n \) be an arbitrary simple tensor in \( V(\Lambda') \). Let \( \Lambda'_n \) be the part of \( \Lambda' \) recording the places in \( v \) at which \( v_n \) appears (so of course \( r + 1 \in \Lambda'_n \)). For any \( j = 1, \ldots, n-1 \) the tensor
\[
s \cdot v = s \cdot (v_{i_1} \otimes \cdots \otimes v_{i_r} \otimes v_n)
\]
belongs to \( V(\Lambda) \), where \( s \in W_n \) is the transposition \( s = (j, n) \). For each \( j = 1, \ldots, n-1 \), the map \( f_j \) from \( V(\Lambda') \) into \( V(\Lambda) \) defined on simple tensors by \( v \mapsto s(v) \), then extended linearly, is injective. Furthermore, the image of each \( f_j \) gives an isomorphic copy of \( V(\Lambda') \) inside \( V(\Lambda) \). Finally, the embedding \( f_n \) of \( V(\Lambda') \) in \( V(\Lambda) \) defined by \( v \mapsto v \) gives another isomorphic copy of \( V(\Lambda') \) in \( V(\Lambda) \). Since \( V(\Lambda) \) is equal to the direct sum of the images of the \( n \) maps \( f_1, \ldots, f_n \), it follows that \( \text{rank}_k V(\Lambda) = n \cdot \text{rank}_k V(\Lambda') \). □

Remark 4.6. It is easy to check that
\[
V(\Lambda') \cong \text{ind}^{W_n}_{W_{n-1}} V(\Lambda'),
\]
the module obtained by inducing \( V(\Lambda') \) from \( W_{n-1} \) to \( W_n \).

Note that, by definition, simple tensors in \( V(\Lambda') \) always have the fixed vector \( v_n \) appearing in place \( r + 1 \). We also note that whenever \( \Lambda \) has more than \( n \) parts there are no simple tensors in \( V(\Lambda') \) of value-type \( \Lambda \), so \( V(\Lambda) = 0 \). On the other hand, it is easy to see that \( V(\Lambda) \neq 0 \) if \( \ell(\Lambda) \leq n \). It follows from Lemma 4.5 that \( V(\Lambda') \neq 0 \) if and only if \( \ell(\Lambda') \leq n \).

Here then are the promised decompositions.

Proposition 4.7. The action of \( W_n \) on \( V^\otimes r \) preserves value-type of simple tensors, so \( V(\Lambda) \) is a left \( kW_n \)-module. Similarly, \( V(\Lambda') \) is a left \( kW_{n-1} \)-module. Furthermore, we have direct sum decompositions
\[
V^\otimes r = \bigoplus_{\ell(\Lambda) \leq n} V(\Lambda), \quad V^\otimes r \otimes v_n = \bigoplus_{\ell(\Lambda') \leq n} V(\Lambda')
\]
where \( \Lambda, \Lambda' \) vary over all set-partitions (with not more than \( n \) parts) of \( \{1, \ldots, r\}, \{1, \ldots, r+1\} \), respectively. The decompositions are multiplicity-free, in the sense that each \( V(\Lambda), V(\Lambda') \) appears exactly once in the direct sum.

Proof. All the claims are easily verified. The point is that the classification of simple tensors by value-type describes the orbits of simple tensors under the left action of \( W_n \). The claims for \( W_{n-1} \) are just variations on this theme. □

The problem with the decompositions in Proposition 4.7 is that the summands are not pairwise non-isomorphic (as \( kW_n \) or \( kW_{n-1} \)-modules).
By looking at examples one quickly observes that $V(\Lambda)$ depends, up to isomorphism, only on the number of parts $\ell(\Lambda)$ and not on $\Lambda$ itself. Similar remarks apply to the $V'(\Lambda')$ in the second decomposition.

To overcome this difficulty, we introduce minimal prototypes for the isomorphism classes that can occur as summands in the above decompositions of tensor space.

**Definition 4.8.** For any $l = 1, \ldots, n$ let $H_n(l)$ be the $kW_n$-submodule of $V^\otimes l$ generated by $v_{n-l+1} \otimes \cdots \otimes v_n$.

Here are some elementary properties of the $H_n(l)$.

**Lemma 4.9.** As left $kW_n$-modules, we have isomorphisms:

(a) $H_n(l) \cong M^{(n-l, 1^l)}$, for any $l = 1, \ldots, n - 1$.

(b) $H_n(n) \cong M^{(1^n)} \cong kW_n$.

(c) $H_n(n-1) \cong H_n(n)$.

**Proof.** As (c) follows from (a), (b) we only need to prove (a), (b). To prove (a), observe that $H_n(l)$ is a transitive permutation module, because its basis elements $\{w \cdot (v_{n-l+1} \otimes \cdots \otimes v_n) \mid w \in W_n\}$ are permuted transitively by the action of $W_n$. The stabiliser of $v_{n-l+1} \otimes \cdots \otimes v_n$ is the Young subgroup $W_{n-l} = \{w \in W_n \mid w(k) = k \text{ for all } k = n - l + 1, \ldots, n\}$. Since

$$W_{n-l} \cong W_{\{1, \ldots, n-l\}} \times W_{\{n-l+1\}} \times \cdots \times W_{\{n\}},$$

this is the Young subgroup indexed by the partition $(n-l, 1^l)$. Hence $H_n(l) \cong \text{ind}_{W_{n-l}}^{W_n} kW_n \cong M^{(n-l, 1^l)}$, and (a) is proved. For (b), observe that the stabiliser of the generator $v_1 \otimes \cdots \otimes v_n$ is the trivial subgroup, which is the Young subgroup indexed by $(1^n)$. For another way to prove (c), observe that the stabiliser of $v_2 \otimes \cdots \otimes v_n$ is also trivial, because any permutation in $W_n$ fixing $n - 1$ points must fix all $n$ points. \qed

**Proposition 4.10.** Let $\Lambda, \Lambda'$ be set-partitions of $\{1, \ldots, r\}, \{1, \ldots, r + 1\}$ respectively, with not more than $n$ parts. Then:

(a) $V(\Lambda) \cong H_n(\ell(\Lambda))$, as left $kW_n$-modules.

(b) $V'(\Lambda') \cong H_{n-1}(\ell(\Lambda') - 1)$, as left $kW_{n-1}$-modules.
Proof. (a) The isomorphism is given by sending each \( v_{i_1} \otimes \cdots \otimes v_{i_l} \) in \( H_n(l) \) to the simple tensor in \( V(\Lambda) \) obtained by writing \( v_{i_k} \) into all tensor places in \( \Lambda_k \), where \( \Lambda = \{ \Lambda_1, \ldots, \Lambda_l \} \).

(b) The proof of (b) is similar to the proof of (a), except that \( v_n \) is fixed wherever it appears. Write \( \Lambda' = \{ \Lambda_1, \ldots, \Lambda_{l+1} \} \) and assume that \( r+1 \) belongs to \( \Lambda_l \), so \( \Lambda_l \) records the places containing a \( v_n \). Then the isomorphism is defined by sending \( v_{i_1} \otimes \cdots \otimes v_{i_{l-1}} \) in \( H_{n-1}(l-1) \) to the simple tensor in \( V'(\Lambda') \) obtained by writing \( v_{i_k} \) into all tensor places in \( \Lambda_k \), for \( k = 1, \ldots, l-1 \), and writing \( v_n \) in the places in \( \Lambda_l \).

Corollary 4.11. For any ring \( \mathbb{k} \), we have isomorphisms

\[
V^{\otimes r} \cong \bigoplus_{1 \leq i \leq \min(n,r)} H_n(i)\{i\}, \quad V^{\otimes r} \otimes v_n \cong \bigoplus_{1 \leq i \leq \min(n-1,r)} H_{n-1}(i)\{i+1\}
\]

as left \( \mathbb{k}W_n \)-modules, \( \mathbb{k}W_{n-1} \)-modules, respectively. The Stirling numbers \( \{r\} \), \( \{r+1\} \) give the multiplicities of the direct summands in the decompositions.

Proof. By Proposition 4.10 the direct summands in Proposition 4.7 are isomorphic to \( H_n(l), H_{n-1}(l) \), where \( 1 \leq l \leq \min(n,r), \min(n-1,r) \) respectively. The number of set partitions \( \Lambda \) of \( \{1, \ldots, r\} \) for which \( \ell(\Lambda) = l \) is given by \( \{l\} \), the Stirling number of the second kind [Sta12, §1.9]. It follows that the number of set partitions \( \Lambda' \) of \( \{1, \ldots, r+1\} \) for which \( \ell(\Lambda') = l \) is given by \( \{r+1\} \).

Remark 4.12. If \( n \leq r, n-1 \leq r \), respectively, then the direct summands in the decompositions in Corollary 4.11 are still not pairwise non-isomorphic. In those cases, we have to take the isomorphism in Lemma 4.9(c) into account. This is worth living with in order to have a uniform formula for the multiplicities of the summands.

As another consequence of these results, we easily obtain the promised sharpening (see Remark 4.2) of Lemma 4.1.

Corollary 4.13. For any unital ring \( \mathbb{k} \), the representations \( \Phi_{n,r}, \Phi_{n,r+1/2} \) are faithful when \( n-1 \leq r, n-2 \leq r \), respectively.

Proof. This follows immediately from the decompositions in Corollary 4.11 and the isomorphisms in Lemma 4.9(b), (c) which imply that \( H_n(n-1) \cong \mathbb{k}W_n, H_{n-1}(n-2) \cong \mathbb{k}W_{n-1} \) are faithful modules.
Remark 4.14. The converse of both implications in Corollary 4.13 also hold, so the given bounds are precise. See (15) in Section 7 which shows that $y_\lambda$ where $\lambda = (n)$ belongs to the annihilator of $H_\alpha(l)$ for any $l < n - 1$.

5 The annihilator of $V^\otimes r$ in characteristic zero

Recall that we always identify $V^\otimes r$ with $V^\otimes r \otimes v_n$ when considering the representation $\Phi_{n,r+1/2} : kW_{n-1} \to \text{End}_k(V^\otimes r)$. We also have the representation $\Phi_{n,r} : kW_n \to \text{End}_k(V^\otimes r)$. From now on we treat the two representations uniformly, writing them as

$$\Phi_{n,r+\varepsilon} : kW_d \to \text{End}_k(V^\otimes r),$$

where $\varepsilon \in \{0, 1/2\}$ and $d = d(n, \varepsilon) := n - 2\varepsilon$. Henceforth, the symbols $\varepsilon$, $d$ will always have these fixed interpretations. We wish to study $\ker \Phi_{n,r+\varepsilon}$, so from now on we always assume that $d > r + 1$, because otherwise $\Phi_{n,r+\varepsilon}$ is faithful, by Corollary 4.13.

In this section we assume that $k$ is a field of characteristic zero. This implies that $kW_d$ is semisimple. By the Artin–Wedderburn theorem and the fact that all irreducible representations of $W_d$ are absolutely irreducible, we have a (split) semisimple decomposition

$$kW_d \cong \bigoplus_{\mu \vdash d} \text{End}_k(S^\mu)$$

where $S^\mu$ is the (irreducible) Specht module indexed by $\mu \vdash d$. The assumption $d > r + 1$ implies that $\min(d, r) = r$, so we may combine the two cases of Corollary 4.11 as: $V^\otimes r \cong \bigoplus_{1 \leq l \leq r} H_d(l)\{r+2\varepsilon\}$. In light of the isomorphism from Lemma 4.9(a), this gives the decomposition

$$V^\otimes r \cong \bigoplus_{\lambda \in \mathcal{H}(d,r)} (M^\lambda)^{m_{\lambda}} \quad (m_{\lambda} > 0)$$

as left $kW_d$-modules, where $\mathcal{H}(d,r) = \{(d-l,1^l) \mid l = 1, \ldots, r\}$. Note that $\mathcal{H}(d,r)$ is a set of hook partitions and the $M^\lambda$ such that $\lambda \in \mathcal{H}(d,r)$ are pairwise non-isomorphic. The multiplicities $m_{\lambda}$ in (10) are given by Stirling numbers, but we only need that they are positive integers.

Definition 5.1. Write $\alpha(d,r) = (d-r, 1^r)$ for the minimum element (with respect to the dominance order) of the set $\mathcal{H}(d,r)$.

If $S$ is a simple module and $M$ is a module satisfying the Jordan–Hölder theorem, write $[M : S]$ for the multiplicity of $S$ in a composition series of $M$. Our next result provides a lower bound on $\ker \Phi_{n,r+\varepsilon}$ in characteristic zero.
Proposition 5.2. Assume that $k$ is a field of characteristic zero. Let $d = n - 2\varepsilon$ and assume that $d > r + 1$, where $\varepsilon \in \{0, 1/2\}$. The set of $\lambda \vdash d$ such that $[V^{\otimes r} : S^\lambda] \neq 0$ is contained in $\{\lambda \vdash d \mid \lambda \succeq \alpha(d, r)\}$. Hence, $\ker \Phi_{n, r + \varepsilon}$ contains an isomorphic copy of $\bigoplus_{\lambda \succeq \alpha(d, r)} \text{End}_k(S^\lambda)$.

Proof. The indexing set $\mathcal{H}(d, r)$ in the decomposition (10) forms a well-ordered chain under the dominance order. By Young’s rule (see for instance [Jam78, 4.13 or 14.1]), for any $\mu \vdash d$, the set of $\lambda \vdash d$ such that $[M^\mu : S^\lambda] \neq 0$ is contained in $\{\lambda \vdash d \mid \lambda \succeq \mu\}$. The first claim follows, since $\{\lambda \succeq \mu \mid \mu \in \mathcal{H}(d, r)\} = \{\lambda \vdash d \mid \lambda \succeq \alpha(d, r)\}$ because $\alpha(d, r)$ is the minimum element of $\mathcal{H}(d, r)$. Hence, as a $kW_d$-module, the decomposition (10) takes the form $V^{\otimes r} \cong \bigoplus_{\lambda \succeq \alpha(d, r)} (S^\lambda)^{n_\lambda}$, where $n_\lambda \geq 0$ is the multiplicity of $S^\lambda$ in the decomposition. The semisimple decomposition $kW_d \cong \bigoplus_{\lambda \vdash d} \text{End}_k(S^\lambda)$ then implies the final statement in the proposition, since the only summands acting non-trivially on $V^{\otimes r}$ are the $\text{End}_k(S^\lambda)$ such that $\lambda \succeq \alpha(d, r)$ and $n_\lambda > 0$.

The following fact from [DN11] can be applied to obtain the opposite inclusion and thus prove equality in Proposition 5.2.

Lemma 5.3 ([DN11 Lemma 6.4]). Assume that $k$ is a field of characteristic zero. For any partitions $\lambda \succeq \mu$ there is an embedding of $M^\lambda$ in $M^\mu$, as $kW_d$-modules.

If $M^\lambda$ embeds in $M^\mu$ then clearly $\text{ann}_{kW_d} M^\lambda \supseteq \text{ann}_{kW_d} M^\mu$.

Proposition 5.4. Assume that $k$ is a field of characteristic zero. Let $d = n - 2\varepsilon$ and assume that $d > r + 1$, where $\varepsilon \in \{0, 1/2\}$. Then:

(a) $\ker \Phi_{n, r + \varepsilon}$ is isomorphic to $\bigoplus_{\lambda \succeq \alpha(d, r)} \text{End}_k(S^\lambda)$.

(b) $\ker \Phi_{n, r + \varepsilon} = \text{ann}_{kW_d} M^{\alpha(d, r)} = \bigcap_{\lambda \succeq \alpha(d, r)} \text{ann}_{kW_d} M^\lambda$.

Proof. (a) Lemma 5.3 implies that we do not change the annihilator by adding extra permutation module terms in the $kW_d$-module decomposition (10), enlarging it to $\bigoplus_{\mu \succeq \alpha(d, r)} (M^\mu)^{m_\mu}$, where $m_\mu := 1$ for any $\mu \notin \mathcal{H}(d, r)$. But then any $S^\lambda$ for $\lambda \vdash d$ such that $\lambda \succeq \alpha(d, r)$ must occur with multiplicity at least one, since $[M^\lambda : S^\lambda] = 1$. This implies that the
annihilator cannot be larger than $\bigoplus_{\lambda \trianglerighteq \alpha(d,r)} \End_k(S^\lambda)$. The equality in part (a) then follows from Proposition 5.2.

(b) By Lemma 5.3, for each $\lambda \trianglerighteq \alpha(d,r)$ we have an embedding $M^\lambda \subseteq M^{\alpha(d,r)}$. It follows that there is an embedding $\text{ann}_k W_d M^\lambda \supseteq \text{ann}_k W_d M^{\alpha(d,r)}$. Hence the intersection

$$\text{ann}_k W_d V^{\otimes r} = \bigcap_{\lambda \trianglerighteq \alpha(d,r)} \text{ann}_k W_d M^\lambda$$

collapses to the single term $\text{ann}_k W_d M^{\alpha(d,r)}$. This proves part (b). 

6 Reformulation of the characteristic zero result

As in Section 5, we still assume that $k$ is a field of characteristic zero. Our standing assumption that $d > r + 1$ remains in force. Finally, we remind the reader that $d = n - 2\varepsilon$, where $\varepsilon \in \{0, 1/2\}$.

It is easy to see by looking at examples that the $y$-basis $Y$ is the right one to use in order to describe the kernel of $\Phi_{n,r+\varepsilon}$ as a cell ideal. For instance, if $n = 3$ and $r = 1$ then it is easy to check that the map $\Phi_{3,1} : kW_3 \to \End(V)$ has kernel generated by the element

$$y_{t(3)t(3)} = \sum_{w \in W_3} \text{sgn}(w) w.$$

Note that this example is compatible with Proposition 5.4(a), which says that the kernel is isomorphic to $\End_k(S^{(1^3)}) = \End_k(\Delta(3))$.

We now reformulate Proposition 5.4 by replacing $\lambda$ by its transpose $\lambda^t$, in light of the identification $\Delta(\lambda) = S^{\lambda^t}$ from Theorem 1.1. Then Proposition 5.4(a) takes the form

$$\ker \Phi_{n,r+\varepsilon} \cong \bigoplus_{\lambda^t \triangleright \alpha(d,r)} \End_k(S^{\lambda^t}) = \bigoplus_{\lambda \not\triangleright \alpha(d,r)} \End_k(\Delta(\lambda))$$

where the rightmost equality follows from the equivalence

$$\lambda^t \not\triangleright \alpha(d,r) \iff \lambda \not\triangleright \alpha(d,r)^t.$$

Note that $\alpha(d,r)^t = (r + 1, 1^{d-r-1}) = \alpha(d, d - r - 1)$. Combining the above with the equality

$$\text{ann}_k W_d V^{\otimes r} = \bigcap_{\lambda \trianglerighteq \alpha(d,r)} \text{ann}_k W_d M^\lambda$$

in Proposition 5.4(b), we obtain the following.
Proposition 6.1. Assume that $k$ is a field of characteristic zero. Let $d = n - 2\varepsilon$ and assume that $d > r + 1$, where $\varepsilon \in \{0, 1/2\}$. Then

$$\ker \Phi_{n,r+\varepsilon} = \bigcap_{\lambda \vdash d, \lambda \geq \alpha(d,r)} \text{ann}_k W_d M^\lambda = k\{y_{st} \mid [s] = [t] \not\in \alpha(d,r)^t\}.$$ 

Proof. Most of the proof is in the remarks preceding the statement. To complete the proof, we only need to observe that in the semisimple case, the cell ideal spanned by all $y_{st}$ for $[s] = [t] \not\in \alpha(d,r)^t$ is isomorphic to $\bigoplus_{\lambda \not\in \alpha(d,r)^t} \text{End}_k(\Delta(\lambda))$. \qed

Note the similarity, and the difference, with Lemma 3 of [Har99]. Later we will show that the description of $\ker \Phi_{n,r+\varepsilon}$ in the rightmost equality of Proposition 6.1 is characteristic-free.

The following characterisation of the key inequalities in the above proposition will be useful in the next section. We write $\text{rows}(\lambda)$, $\text{cols}(\lambda)$ for the number of rows, columns in the Young diagram of $\lambda$, respectively.

Lemma 6.2. Let $\lambda \vdash d$. Then:

(a) $\lambda \trianglerightequal \alpha(d,r)$ $\iff$ $\text{cols}(\lambda) \geq d - r$.

(b) $\lambda \trianglerightequal \alpha(d,r)^t$ $\iff$ $\text{rows}(\lambda) \geq d - r$.

Remark 6.3. Part (b) implies that $\lambda \not\trianglerightequal \alpha(d,r)^t$ $\iff$ $\text{rows}(\lambda) < d - r$.

Proof. (a) Since $\alpha(d,r) = (d - r, 1^r)$, it follows by the definition of the dominance order that $\lambda \triangleright equal \alpha(d,r)$ if and only if

$$\lambda_1 \geq d - r, \quad \lambda_1 + \lambda_2 \geq d - r + 1, \quad \ldots, \quad \lambda_1 + \cdots + \lambda_{r+1} \geq d.$$ 

Since $\lambda_1 = \text{cols}(\lambda)$, it follows that $\lambda$ has at least $d - r$ columns if and only if $\lambda \triangleright equal \alpha(d,r)$. This proves (a).

(b) This follows from (a), since for $\mu, \nu \vdash d$ we have $\mu \triangleright equal \nu$ $\iff$ $\mu^t \trianglerightequal \nu^t$. First, replace $\lambda$ with $\mu$ in (a) to get $\mu \triangleright equal \alpha(d,r) \iff \text{cols}(\mu) \geq d - r$. This is equivalent to the statement

$$\mu^t \trianglerightequal \alpha(d,r)^t \iff \text{cols}(\mu) \geq d - r.$$ 

Using the fact that $\text{cols}(\mu) = \text{rows}(\mu^t)$, we obtain the desired result by setting $\lambda = \mu^t$ in the above. \qed
Suppose that $\Omega$ is any set of partitions of $d$. For convenience of notation, we set $A = \mathbb{k}W_d$. Following Graham and Lehrer, we define

$$A^\nu[\Omega] = \sum_{\lambda \in \Omega: [s] = [t] = \lambda} \mathbb{k}y_{\lambda}.$$ 

A set $\Omega$ of partitions of $d$ is \textit{upward-closed} with respect to the dominance order if $\lambda \in \Omega$ and $\mu \triangleright \lambda$ (for $\mu \triangleright d$) always implies $\mu \in \Omega$. It is clear that the set

$$\Omega = \{\lambda \triangleright d \mid \lambda \ntriangleleft \alpha(d, r)^t\}$$

is upward-closed, because if $\lambda$ is a partition of strictly fewer than $d - r$ parts and if $\mu \triangleright \lambda$ then the diagram of $\mu$ is obtained from the diagram of $\lambda$ by moving boxes up, which cannot increase the number of rows. Alternatively, if $\lambda \ntriangleleft \alpha(d, r)^t$ and if $\mu \triangleright \lambda$ then the assumption $\mu \leq \alpha(d, r)^t$ implies that $\lambda \leq \mu \leq \alpha(d, r)^t$, which forces $\lambda \leq \alpha(d, r)^t$, a contradiction.

The importance of this is that Graham and Lehrer proved that the set $A[\Omega]$ is always an ideal in the cellular algebra $A$, provided only that the set $\Omega$ is closed with respect to the ordering of the cells. In our setting, this result translates into the following statement.

\textbf{Proposition 6.4} (\cite[Lemma (1.5)]{GL}). For the upward closed set of partitions $\Omega = \{\lambda \triangleright d \mid \lambda \ntriangleleft \alpha(d, r)^t\}$, the corresponding span

$$A^\nu[\Omega] = A^\nu[\ntriangleleft \alpha(d, r)^t]$$

is a cell ideal in $A = \mathbb{k}W_d$.

The cell ideal $A^\nu[\ntriangleleft \alpha(d, r)^t] = \ker \Phi_{n, r + \epsilon}$ in Proposition 6.1.

\section{The annihilator in general}

Now we revert back to the general case, where $\mathbb{k}$ is once again an arbitrary unital ring. Note that Proposition 6.4 holds in this generality. We continue to set $A = \mathbb{k}W_d$.

Let $v = v_{i_1} \otimes \cdots \otimes v_{i_l}$ in $H_d(l)$ be a simple tensor with distinct tensor factors (i.e., $i_\alpha \neq i_\beta$ for $1 \leq \alpha \neq \beta \leq l$). We start by computing $y_{\lambda} \cdot v$, where $\lambda \triangleright d$ and $1 \leq l \leq d$. (See equation (1) for the definition of $y_{\lambda}$.) Let

$$W_d^v = \{w \in W_d \mid w \cdot v = v\}$$

be the stabiliser of $v$ in $W_d$. Clearly we have $W_d^v = W_B$ where $B = \{1, \ldots, d\} \setminus \{i_1, \ldots, i_l\}$. Let $W_\lambda$ be the Young subgroup determined by $\lambda$,
and write it as $W_{C_1} \times \cdots \times W_{C_k}$, where $\lambda$ has $k$ parts. Here $C_j$ is the subset of $\{1, \ldots, d\}$ defined by the numbers in the $j$th row of $t^\lambda$. Note that \{C_1, \ldots, C_k\} is a set partition of $\{1, \ldots, d\}$. We have

$$W_\lambda \cap W_B = (W_{C_1} \times \cdots \times W_{C_k}) \cap W_B = W_{C_1 \cap B} \times \cdots \times W_{C_k \cap B}. \quad (13)$$

The stabiliser of $v$ in $W_\lambda$ is $S = W_\lambda \cap W^v_d = W_\lambda \cap W_B$ as above. Fix a left coset decomposition $w_1S \sqcup w_2S \sqcup \cdots \sqcup w_tS = W_\lambda$ of $W_\lambda/S$, where \{w_1, \ldots, w_t\} is a set of coset representatives. Then by the definition of $y_\lambda$ we have

$$y_\lambda \cdot v = \sum_{i=1}^t \sum_{s \in S} \text{sgn}(w_i s) \, w_i s \cdot v = \sum_{i=1}^t \text{sgn}(w_i) \left( \sum_{s \in S} \text{sgn}(s) \right) \, w_i \cdot v. \quad (14)$$

This proves that if we set $F_S = \sum_{s \in S} \text{sgn}(s)$ then we have

$$y_\lambda \cdot v = F_S \sum_{i=1}^t \text{sgn}(w_i) \, w_i \cdot v. \quad (15)$$

We note that $F_S$ is a scalar depending only on $S$. Since $S$ is a product of symmetric groups by (13), it follows that $F_S$ is either zero or one, with the latter case occurring if and only if $S$ is the trivial subgroup. We have shown that:

$$S = W^v_d \cap W_\lambda \neq \{1\} \implies y_\lambda \cdot v = 0. \quad (15)$$

From the above analysis, we now obtain a lower bound for the annihilator of $V \otimes r$ as a $kW_d$-module, where $d = n - 2\varepsilon$ as usual. Later we will show the bound is precise.

**Proposition 7.1.** Let $k$ be an arbitrary unital ring and assume that $d > r+1$. Let $d = n-2\varepsilon$, where $\varepsilon \in \{0, 1/2\}$. Then the kernel of $\Phi_{n,r+\varepsilon}$ contains the cell ideal $A[\not\exists \alpha(d, r)]$, where $A = kW_d$.

**Proof.** Let $\lambda \vdash d$ have fewer than $d-r$ parts. In light of Corollary 4.11, we need to show that $y_{st} \cdot v = 0$, for any $v \in H_d(l)$, where $1 \leq l \leq r-2\varepsilon$. Since $y_{st} = d(s)^{-1}y_\lambda d(t)$ it clearly suffices to show that $y_\lambda \cdot v = 0$ for any such $v$. By (15), this will follow if we can show that $W^v_d \cap W_\lambda$ is not trivial. By (13), we have

$$W^v_d \cap W_\lambda = W_\lambda \cap W_B = W_{C_1 \cap B} \times \cdots \times W_{C_k \cap B}$$

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where $W_\lambda = W_{C_1} \times \cdots \times W_{C_k}$ and $B = \{1, \ldots, d\} \setminus \{i_1, \ldots, i_l\}$. Since $\{1, \ldots, d\} = C_1 \sqcup \cdots \sqcup C_k$, we have

$$B = (C_1 \cap B) \sqcup \cdots \sqcup (C_k \cap B).$$

Furthermore, we have $|B| = d - l$. The condition $l \leq r$ (from above) forces

$$|B| = d - l \geq d - r > k.$$ 

Hence at least one $C_j \cap B$ has more than one element, and thus $W_v \cap W_\lambda$ is not trivial.

To obtain the opposite inclusion, we will adapt a result of Härterich.

**Proposition 7.2.** Suppose that $k$ is an integral domain. For any $\mu \vdash d$,

$$\bigcap_{\lambda \vdash d, \lambda \geq \mu} \operatorname{ann}_A M^\lambda$$

is spanned by $\{y_{st} | s, t \text{ standard, } [s] = [t] \not\vdash \mu^t\}$.

**Proof.** This can be proved in exactly the same way that Lemma 3 of [Här 99] was proved. The difficult calculation involved in the proof is due to Murphy and is given in Lemmas 4.12 and 4.16 of [Mur 95]. One then proceeds (as in [Här 99]) by induction on the dominance order on (pairs of) tableaux. \qed

**Remark 7.3.** Observe that the sets $A^\mu[\geq \mu^t]$ and $A^\mu[\not\geq \mu^t]$ are both cell ideals, since both sets $\{\lambda \vdash d | \lambda \geq \mu^t\}$ and $\{\lambda \vdash d | \lambda \not\geq \mu^t\}$ are upward-closed sets of partitions. (See the remarks before Proposition 6.4.)

To finish, we will specialise $\mu$ to $\alpha(d, r)$ in Proposition 7.2. We also need one more fact. We need to show that the intersection of annihilators in Proposition 7.2 in the case $\mu = \alpha(d, r)$ is in fact the same as the annihilator of $V^{\otimes r}$. This is far from obvious in general, although we already proved this is so if $k$ is a field of characteristic zero. If Lemma 5.3 were true over any ground ring $k$ then we would be able to apply the same argument that produced Proposition 5.4(a), but unfortunately there is an example in [DN11] showing that Lemma 5.3 can fail in positive characteristic.

It turns out, however, that there is a version of Lemma 5.3 that holds over any ring $k$, where the second partition is taken to be $\alpha(d, r)$.

**Proposition 7.4.** For any ring $k$, and any $\lambda \vdash d$ such that $\lambda \geq \alpha(d, r)$, we have an embedding $M^\lambda \subseteq M^{\alpha(d, r)}$, as $kW_d$-modules.
Proof. Write $A = kW_d$ as before. For any $\lambda \vdash d$, the permutation module $M^{\lambda}$ is isomorphic to the left ideal $Ax_{\lambda}$. For ease of typography set $\mu = \alpha(d, r)$, and assume that $\lambda \trianglerighteq \mu$. Then by applying [Mur95, Lemma 4.1] we see that $x_\mu$ must divide $x_{\lambda} = x_t$ for $t = t^{\lambda}$ the canonical $\lambda$-tableaux; i.e., there is some $z \in A$ such that $x_{\lambda} = zx_\mu$. This immediately implies that $Ax_{\lambda} = Azx_\mu \subseteq Ax_\mu$, as required.

Now we finally obtain our main result.

Theorem 7.5. Let $d = n - 2\varepsilon$, where $\varepsilon \in \{0, 1/2\}$. Set $A = kW_d$. For any integral domain $k$, the kernel of $\Phi_{n, r+\varepsilon}$ is equal to the cell ideal

$$A[\not\in \alpha(d, r)^{\lambda}] = k\{y_{st} \mid s, t \text{ standard, } [s] = [t] \not\in \alpha(d, r)^{\lambda}\}.$$  

The image of the set

$$k\{y_{st} \mid s, t \text{ standard, } [s] = [t] \trianglerighteq \alpha(d, r)\}$$

in $A/(\ker \Phi_{n, r+\varepsilon})$ is a cellular basis of $\text{im} \Phi_{n, r+\varepsilon}$. Both the kernel $\ker \Phi_{n, r+\varepsilon}$ and image $\text{im} \Phi_{n, r+\varepsilon}$ are cellular algebras. The cell-poset for the kernel (respectively image) is the set of partitions of strictly fewer (greater) than $d - r$ parts. The image and kernel of $\Phi_{n, r+\varepsilon}$ are free over $k$ of rank which is independent of $k$. Furthermore, $\ker \Phi_{n, r+\varepsilon} = \text{ann}_{kW_d} V^\otimes r = \text{ann}_{kW_d} M^{\alpha(d, r)}$.

Proof. This is just a matter of putting the various pieces together. We use Proposition 7.4 to show that the annihilator

$$\text{ann}_A V^\otimes r = \bigcap_{\lambda \in \mathcal{H}(d, r)} \text{ann}_A M^{\lambda}$$

remains unchanged when we include extra terms of the form $\text{ann}_A M^{\lambda}$ for any $\lambda \trianglerighteq \alpha(d, r)$. This implies that

$$\text{ann}_A V^\otimes r = \bigcap_{\lambda \trianglerighteq \alpha(d, r)} \text{ann}_A M^{\lambda}.$$  

Now the first claim follows from Proposition 7.2. The remaining claims follow immediately.

By combining Theorem 7.5 with Schur–Weyl duality, we obtain the following consequence.

Corollary 7.6. Let $\varepsilon \in \{0, 1/2\}$. For any integral domain $k$, the algebra $\text{End}_{P_{r+\varepsilon}(n)}((V^\otimes r)$ is cellular.
Proof. By the main result of [BDM18], that Schur–Weyl duality holds over an arbitrary unital ring $\mathbb{k}$, the representation $\Phi_{n,r+\varepsilon}$ surjects onto the algebra $\text{End}_{\mathbb{P}_{r+\varepsilon}(n)}(V^{\otimes r})$. By Theorem 7.5 that image is cellular. □

References


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