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Restriction of Odd Degree Characters of $S_n$

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Abstract. Let $n$ and $k$ be natural numbers such that $2^k < n$. We study the restriction to $S_{n-2^k}$ of odd-degree irreducible characters of the symmetric group $S_n$. This analysis completes the study begun in [Ayyer A., Prasad A., Spallone S., Sémin. Lothar. Combin. 75 (2015), Art. B75g, 13 pages] and recently developed in [Isaacs I.M., Navarro G., Olsson J.B., Tiep P.H., J. Algebra 478 (2017), 271–282].

Key words: characters of symmetric groups; hooks in partitions

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1 Introduction

Let $n$ be a natural number, and let $\chi$ be an irreducible character of odd degree of the symmetric group $S_n$. Then there exists a unique odd-degree irreducible constituent of the restriction $\chi_{S_{n-1}}$. This interesting fact was discovered recently in [1]. The result had immediate applications in the study of natural correspondences of characters of finite groups (see for example [2]). In [3, Theorem A] the result mentioned above was generalized, by showing that given any $k \in \mathbb{N}$ such that $2^k < n$, there exists a unique odd-degree irreducible constituent $f_k^n(\chi)$ of $\chi_{S_{n-2^k}}$ appearing with odd multiplicity. The main goal of this article is to study for all $n, k \in \mathbb{N}$ the map

$$f_k^n : \text{Irr}_2(S_n) \rightarrow \text{Irr}_2(S_{n-2^k}),$$

naturally defined by Theorem A of [3]. All our results are proved using a description of $f_k^n$ in terms of the natural partition labels of the involved irreducible characters.

Before describing the main results of this paper, we introduce some vocabulary. If $2^k$ appears in the binary expansion of $n$ we say that $2^k$ is a binary digit of $n$. Similarly we say that two natural numbers $m$ and $n$ are 2-disjoint if they do not have any common binary digit. On the other hand, if $m \leq n$ and all the binary digits of $m$ appear in the binary expansion of $n$, then we say that $m$ is a binary subsum of $n$. This will be denoted by $m \subseteq_2 n$. Let $\nu_2(n)$ be the exponent of the highest power of 2 dividing the integer $n$.

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A question raised in [3] may be phrased as: For which \( n \) and \( k \) is \( f_k^n \) surjective? The authors showed that \( f_k^n \) is surjective whenever \( 2^k \) is a binary digit of \( n \), and they observed that otherwise \( f_k^n \) could be both surjective or not (see [3, Proposition 4.5 and Remark 4.6]). In this paper we answer the question of surjectivity completely with the following result.

**Theorem A.** Let \( n \in \mathbb{N} \), \( k \in \mathbb{N}_0 \) be such that \( 2^k < n \). Let \( d(n, k) = \nu_2 \left( \left\lfloor \frac{n}{2^k} \right\rfloor \right) \).

- If \( k = 0 \) then \( f_k^n \) is surjective if and only if \( d(n, k) \leq 2 \).
- If \( k > 0 \) then \( f_k^n \) is surjective if and only if \( d(n, k) \leq 1 \).

Theorem A is a consequence of Theorem 3.5 below, which describes the images of the maps \( f_k^n \).

For all \( n \in \mathbb{N} \), \( k \in \mathbb{N}_0 \) with \( 2^k < n \) and any \( \psi \in \text{Irr}_{2^k}(\mathcal{S}_{n-2^k}) \) we define the set

\[
\mathcal{E}(\psi, 2^k) = \{ \chi \in \text{Irr}_{2^k}(\mathcal{S}_n) \mid f_k^n(\chi) = \psi \},
\]

and set \( e(\psi, 2^k) = |\mathcal{E}(\psi, 2^k)| \). We show in Corollary 3.8 that the maps \( f_k^n \) are regular on their images. This means that for any \( \psi \) in the image of \( f_k^n \), the number \( e(\psi, 2^k) \) depends only on \( n \) and \( k \) and not on the specific \( \psi \). We also give a complete description of those \( \psi \in \text{Irr}_{2^k}(\mathcal{S}_{n-2^k}) \) such that \( e(\psi, 2^k) = 0 \), in Theorem 3.5.

In the final part of the paper we study commutativity. For convenience, we sometimes denote \( f_k^n \) just by \( f_k \), when the natural number \( n \) is clear from the context. Then, for \( k, \ell \in \mathbb{N}_0 \), \( k < \ell \), such that \( 2^k + 2^\ell \leq n \), we may ask: when is \( f_k f_\ell = f_\ell f_k \)? or more specifically: when is \( f_k^{n-2^k} f_\ell^{n-2^\ell} = f_\ell^{n-2^k} f_k^{n-2^\ell} \)? In [3, Proposition 4.3] it was proved that \( f_k f_\ell = f_\ell f_k \) whenever \( 2^\ell < n < 2^{\ell+1} \). This is the case \( \ell = t \) in our second main result, which answers the question completely.

**Theorem B.** Let \( n = 2^t + m \) where \( 0 \leq m < 2^t \). Suppose that \( k, \ell \) satisfy \( 0 \leq k < \ell \leq t \) and \( 2^k + 2^\ell \leq n \). Then, with the exception of the case \( n = 6, k = 0, \ell = 1 \),

\[
f_k f_\ell = f_\ell f_k \text{ if and only if } 2^k > m \text{ or } \ell = t.
\]

## 2 Notation and background

Let \( n \) be a natural number. We let \( \text{Irr}(\mathcal{S}_n) \) denote the set of irreducible characters of \( \mathcal{S}_n \) and \( \mathcal{P}(n) \) the set of partitions of \( n \). The notation \( \lambda \in \mathcal{P}(n) \) is sometimes replaced by \( \lambda \vdash n \) and we write \( |\lambda| = n \). There is a natural correspondence \( \lambda \leftrightarrow \chi^\lambda \) between \( \mathcal{P}(n) \) and \( \text{Irr}(\mathcal{S}_n) \). We say then that \( \lambda \) labels \( \chi^\lambda \). We denote by \( \text{Irr}_{2^k}(\mathcal{S}_n) \) the set of irreducible characters of \( \mathcal{S}_n \) of odd degree. If \( \chi^\lambda \in \text{Irr}_{2^k}(\mathcal{S}_n) \) we say that \( \chi^\lambda \) is an odd character, we call \( \lambda \) an odd partition of \( n \) and write \( \lambda \vdash_o n \). Also the empty partition will be considered as an odd partition.

**Remark 2.1.** Let \( n, k \) be such that \( 2^k < n \). In [3, Theorem A and Proposition 4.2] it is shown that the map \( f_k^n : \text{Irr}_{2^k}(\mathcal{S}_n) \rightarrow \text{Irr}_{2^k}(\mathcal{S}_{n-2^k}) \) may be described in terms of the odd partitions labelling the odd characters as follows:

\[
f_k^n(\chi^\lambda) = \chi^\mu \iff \mu \vdash_o n - 2^k \text{ can be obtained from } \lambda \vdash_o n \text{ by removing a } 2^k\text{-hook}.
\]

Correspondingly we write (by abuse of notation) \( f_k^n(\lambda) = \mu \). In fact when \( \lambda \) is odd, there is only one \( 2^k\)-hook of \( \lambda \) whose removal leads again to an odd partition; we will refer to such a hook as an odd hook of \( \lambda \). This combinatorial description of \( f_k^n \) will be used throughout this paper, and we will regard \( f_k^n \) also as a map between the corresponding sets of odd partitions. Also, for \( \mu \vdash_o n - 2^k \) we set \( e(\mu, 2^k) = e(\chi^\mu, 2^k) \).
We need some concepts and basic facts concerning hooks in partitions. For any integer \( e \in \mathbb{N} \) we denote by \( C_e(\lambda) \) and \( Q_e(\lambda) \) the \( e \)-core and the \( e \)-quotient of \( \lambda \), respectively. Then \( Q_e(\lambda) = (\lambda_0, \ldots, \lambda_{e-1}) \) is an \( e \)-tuple of partitions satisfying \( n = |C_e(\lambda)| + e \sum_{i=0}^{e-1} |\lambda_i| \). It is well-known that a partition is uniquely determined by its \( e \)-core and \( e \)-quotient (we refer the reader to [6] or [4, Chapter 2.7] for a detailed discussion on this topic).

Let \( H_e(\lambda) \) be the set of hooks of \( \lambda \) having length divisible by \( e \), and let \( \mathcal{H}(Q_e(\lambda)) = \bigcup_{i=0}^{e-1} H(\lambda_i) \).

As explained in [6, Theorem 3.3], there is a bijection between \( H_e(\lambda) \) and \( \mathcal{H}(Q_e(\lambda)) \) mapping hooks in \( \lambda \) of length \( ex \) to hooks in the quotient of length \( x \). Moreover, the bijection respects the process of hook removal. Namely, the partition \( \mu \) obtained by removing an \( ex \)-hook from \( \lambda \) is such that \( C_e(\mu) = C_e(\lambda) \) and the \( e \)-quotient of \( \mu \) is obtained by removing an \( x \)-hook from one of the partitions involved in \( Q_e(\lambda) \).

For \( e = 2 \) we want to repeat the process of taking 2-cores and 2-quotients to obtain the 2-quotient tower \( Q_2(\lambda) \) and the 2-core tower \( C_2(\lambda) \) of \( \lambda \). They have rows numbered by \( k \geq 0 \).

The \( k \)-th row \( Q_2^{(k)}(\lambda) \) of \( Q_2(\lambda) \) contains \( 2^k \) partitions \( \lambda_i^{(k)} \), \( 0 \leq i \leq 2^k - 1 \), and the \( k \)-th row \( C_2^{(k)}(\lambda) \) of \( C_2(\lambda) \) contains the 2-cores of these partitions in the same order, i.e., \( C_2(\lambda^{(k)}) \), \( 0 \leq i \leq 2^k - 1 \).

The 0th row of \( Q_2(\lambda) \) contains \( \lambda = \lambda_0^{(0)} \) itself, row 1 contains the partitions \( \lambda_0^{(1)}, \lambda_1^{(1)} \) occurring in the 2-quotient \( Q_2(\lambda) \), row 2 contains the partitions occurring in the 2-quotients of partitions occurring in row 1, and so on. Specifically we have \( Q_2^{(k)}(\lambda^{(k)}) = (\lambda_{2i}^{(k+1)}, \lambda_{2i+1}^{(k+1)}) \) for \( i \in \{0, 1, \ldots, 2^k - 1\} \). We remark that the \( 2^k \) partitions in \( Q_2^{(k)}(\lambda) \) are the same as those in the \( 2^k \)-quotient \( Q_{2^k}(\lambda) \) of \( \lambda \), but in a different order for \( k \geq 2 \).

We also introduce the \( k \)-data \( D_2^{(k)}(\lambda) \) of \( \lambda \). This is a table containing the following \( k+1 \) rows: the \( k \) rows \( C_2^{(j)}(\lambda) \), \( j = 0, \ldots, k-1 \), and in addition the row \( Q_2^{(k)}(\lambda) \).

**Remark 2.2.** A partition \( \lambda \) may be recovered from its 2-core tower. For \( k > 0 \), it may also be recovered from the knowledge of the \( k \)-data \( D_2^{(k)}(\lambda) \) of \( \lambda \), because the rows \( C_2^{(l)}(\lambda) \) with \( l \geq k \) of \( C_2(\lambda) \) consist of the 2-core towers of the partitions in \( Q_2^{(k)}(\lambda) \).

**Lemma 2.3.** Suppose that \( \lambda \vdash n - 2^k \) and \( \mu \vdash n \). The following are equivalent.

(i) \( \lambda \) is obtained from \( \mu \) by removing a \( 2^k \)-hook.

(ii) The \( k \)-data \( D_2^{(k)}(\mu) \) and \( D_2^{(k)}(\lambda) \) coincide, except that for one \( i \in \{0, \ldots, 2^k - 1\} \) \( \lambda_i^{(k)} \) is obtained from \( \mu_i^{(k)} \) by removing a 1-hook.

**Proof.** A \( 2^k \)-hook \( H_0 \) in \( \mu \) corresponds in a canonical way to a \( 2^{k-1} \)-hook \( H_1 \) in a partition in \( Q_2^{(1)}(\mu) \), i.e., in row 1 of the 2-quotient tower \( Q_2(\mu) \). Continuing we see that \( H_0 \) corresponds in a canonical way to a 1-hook \( H_k \) in a partition \( \mu_i^{(k)} \) in \( Q_2^{(k)}(\mu) \), row \( k \) of \( Q_2(\mu) \). If \( \lambda \) is obtained by removing \( H_0 \) from \( \mu \), this corresponds to \( \lambda_i^{(k)} \) being obtained by removing the 1-hook \( H_k \) from \( \mu_i^{(k)} \) (by repeated applications of [6, Theorem 3.3]). Apart from this the rows \( Q_2^{(k)}(\mu) \) and \( Q_2^{(k)}(\lambda) \) coincide. Note also that the rows \( C_2^{(j)}(\mu) \) and \( C_2^{(j)}(\lambda) \) coincide for \( j = 0, \ldots, k-1 \), since the removal of the hooks \( H_j \) of even length do not change the 2-cores. \( \blacksquare \)

Odd-degree characters of \( \mathfrak{S}_n \) and thus odd partitions were completely described in [5]. We restate this result in a language which is convenient for our purposes. We let \( c_2^{(k)}(\lambda) \) be the sum of the cardinalities of the partitions in the \( k \)-th row \( C_2^{(k)}(\lambda) \) of \( C_2(\lambda) \).

**Lemma 2.4 ([5]).** Let \( \lambda \) be a partition. Then \( \lambda \) is odd if and only if \( c_2^{(k)}(\lambda) \leq 1 \) for all \( k \geq 0 \).

It may be decided from the \( k \)-data \( D_2^{(k)}(\lambda) \) whether \( \lambda \) is odd. The case \( k = 1 \) of the following result appeared in [3, Lemma 4.1] and also in [1, Lemma 6].
Theorem 2.5. Let $\lambda \vdash n$, and let $k \geq 0$ be fixed. Consider $Q_2^{(k)}(\lambda) = (\lambda_i^{(k)})$. Then $\lambda$ is odd if and only if the following conditions are all fulfilled:

(i) $c_2^{(j)}(\lambda) \leq 1$ for all $j < k$.
(ii) The partitions $\lambda_i^{(k)}$, $0 \leq i \leq 2^k - 1$, are all odd.
(iii) The numbers $|\lambda_i^{(k)}|$, $0 \leq i \leq 2^k - 1$, are pairwise 2-disjoint.

In this case $\sum_{i \geq 0} |\lambda_i^{(k)}| = \left\lceil \frac{n}{2^k} \right\rceil$.

Proof. This is proved by induction on $k \geq 0$, using Remark 2.2 and Lemma 2.4. ■

We illustrate the result above by giving an example.

Example 2.6. Let $n = 15$ and take $\lambda = (5, 4, 2^2, 1^2) \vdash 15$. To decide whether $\lambda$ is odd, we choose $k = 2$ and compute the 2-data $D_2^{(2)}(\lambda)$. The 2-core is $C_2(\lambda) = (1)$, giving $C_2^{(0)}(\lambda) = ((1))$. Furthermore, the 2-quotient is $Q_2(\lambda) = ((2^2, 1^2), (1))$, and computing the 2-cores $C_2((2^2, 1^2)) = (0), C_2((1)) = (1)$, we obtain the next row: $C_2^{(1)}(\lambda) = ((0), (1))$. The 2-quotients are $Q_2((2^2, 1^2)) = ((1^2), (1)), Q_2((1)) = ((0), (0))$; hence the final row of the 2-data table is obtained as $Q_2^{(2)}(\lambda) = ((1^2), (1), (0), (0))$.

We visualize $D_2^{(2)}(\lambda)$ like this:

$C_2^{(0)}(\lambda)$: \begin{align*}
\left(\begin{array}{c}
1
\end{array}\right)
\end{align*}

$C_2^{(1)}(\lambda)$: \begin{align*}
\left(\begin{array}{cccc}
0 & (0) & (1) & (0)
\end{array}\right)
\end{align*}

$Q_2^{(2)}(\lambda)$: \begin{align*}
\left(\begin{array}{cccc}
1 & (1) & (0) & (0)
\end{array}\right)
\end{align*}

Theorem 2.5 shows that $\lambda$ is odd and thus it contains a unique odd 4-hook. Again using the theorem, it is clear that removing this 4-hook corresponds to the second partition (1) in $Q_2^{(2)}$ being replaced by (0). Thus, removing the corresponding 4-hook of $\lambda$ we obtain the odd partition $\mu = (3, 2^2, 1^2) \vdash 11$ with the property that $D_2^{(2)}(\lambda)$ and $D_2^{(2)}(\mu)$ differ only in their final row.

Remark 2.7. Using the construction of partitions from their 2-cores and 2-quotients already mentioned, the criterion above can be applied to construct all odd partitions of $n$ with a specific $k$th row in the 2-quotient tower. For this, let $n, k \in \mathbb{N}$, and take any sequence of odd partitions $\nu_i$, $0 \leq i \leq 2^k - 1$, such that the numbers $|\nu_i|$ are pairwise 2-disjoint, and $\sum_{i \geq 0} |\nu_i| = \left\lceil \frac{n}{2^k} \right\rceil$.

Then there are exactly $\prod_{m < k} 2^m$ odd partitions $\lambda$ of $n$ with $Q_2^{(k)}(\lambda) = (\nu_i)$, obtained by choosing one 2-core in row $m$ of the $k$-data table to be (1), for each $m < k$ such that $2^m \leq n$.

The following easy consequence of Theorem 2.5 will be used repeatedly.

Lemma 2.8. Let $2^t$ be the largest binary digit of $n$. A partition $\lambda$ of $n$ is odd if and only if $\lambda$ contains a unique $2^t$-hook and the partition obtained from $\lambda$ by removing this $2^t$-hook is an odd partition of $n - 2^t$.

3 Surjectivity and regularity

The aim of this section is to study the images of the maps $f_n^k$ for all $n, k$ such that $2^k \leq n$. For this purpose we introduce the concept of $d$-good partitions (see Definition 3.1 below). This will allow us to prove Theorem 3.5 (describing the images) and thus Theorem A (describing exactly when $f_n^k$ is surjective) and to show that the maps $f_n^k$ are always regular on their image (see Corollary 3.8).
Definition 3.1. Let \( d \geq 0 \). We call an odd partition \( \lambda \) \( d \)-good, if

(i) \( |\lambda| \equiv 2^d - 1 \mod 2^{d+1} \).

(ii) \( C_{2^d}(\lambda) \) is a hook partition.

Let us remark that condition (i) may be reformulated as

\[(i^*) \quad \nu_2(|\lambda| + 1) = d.\]

In particular, if \( \lambda \) is \( d \)-good, then \(|\lambda|\) is odd if and only if \( d > 0 \).

The relevance of \( d \)-good partitions in our context is illuminated by the following reformulation of [1, Theorem 2]:

Lemma 3.2. Let \( \lambda \vdash_o n \). Let \( d = \nu_2(n + 1) \). Then \( e(\lambda, 1) \neq 0 \) if and only if \( \lambda \) is \( d \)-good. In this case, \( e(\lambda, 1) = 1 \) if \( d = 0 \), and \( e(\lambda, 1) = 2 \) if \( d > 0 \).

Lemma 3.3. Let \( \lambda \) be an odd partition, and let \( d \geq 0 \). Then the following hold.

1. For \( d \leq 2 \), \( \lambda \) is \( d \)-good if and only if \(|\lambda| \equiv 2^d - 1 \mod 2^{d+1} \).
2. If \( \lambda \) is \( d \)-good, then \( C_{2^d}(\lambda) \) is a partition of \( 2^d - 1 \).

Proof. If the odd partition \( \lambda \) is \( d \)-good, then \(|\lambda| = (2^d - 1) + m \) where the binary digits of \( m \) are at least \( 2^d \). The hooks of \( \lambda \) corresponding to the binary digits of \( m \) may be decomposed into \( 2^d \)-hooks and thus do not contribute to \( C_{2^d}(\lambda) \). Thus \(|C_{2^d}(\lambda)| = 2^d - 1 \). This shows (2). For \( d = 0, 1, 2 \) we have \(|C_{2^d}(\lambda)| = 0, 1 \) and 3, respectively. Since all partitions of 0, 1 and 3 are hook partitions, (1) follows.

Definition 3.4. If \( 2^k \leq n \), we define \( d(n, k) = \nu_2\left(\left\lfloor \frac{n}{2^k} \right\rfloor \right) \). Thus \( d(n, k) \) is the smallest integer \( d \geq 0 \) satisfying the condition \( 2^{k+d} \leq n \). In particular, \( d(n, k) = 0 \) if and only if \( 2^k \leq n \). Moreover, we may write \( \left\lfloor \frac{n}{2^k} \right\rfloor = 2^{d(n,k)} + m(n,k) \) where \( 2^{d(n,k)+1} | m(n,k) \).

As mentioned in the introduction, the results in [3] show that \( f_k^n \) is a surjective \((2^k\to 1)\)-map whenever \( 2^k \leq n \), i.e., \( d(n,k) = 0 \). In the spirit of [1, Theorem 2], we now give a characterization of the image of the map \( f_k^n \) for all \( n, k \) such that \( 2^k < n \).

Theorem 3.5. Let \( n \in \mathbb{N}, k \in \mathbb{N}_0 \) be such that \( 2^k < n \). Let \( \lambda \vdash_o n - 2^k \). Then \( e(\lambda, 2^k) \neq 0 \) if and only if there exists a \( d(n, k) \)-good partition in the \( k \)th row of \( Q_2(\lambda) \). In this case, \( e(\lambda, 2^k) = 2^k \) if \( d(n, k) = 0 \), and \( e(\lambda, 2^k) = 2 \) if \( d(n, k) > 0 \).

Proof. If \( k = 0 \) then the statement follows from Lemma 3.2. Hence assume that \( k \geq 1 \). Let \( d = d(n, k) \). By assumption \( \left\lfloor \frac{n}{2^k} \right\rfloor = 2^d + m \), where the binary digits of \( m \) are at least \( 2^{d+1} \). Thus \( \left\lfloor \frac{n-2^k}{2^k} \right\rfloor = (2^d - 1) + m \).

Suppose first that \( e(\lambda, 2^k) \neq 0 \) and that \( \mu \vdash_0 n \) satisfies \( f_k(\mu) = \lambda \). From Remark 2.1 and Lemma 2.3 we get that there exists an \( i \in \{0, 1, \ldots, 2^k - 1\} \) such that \( f_0(\mu^{(k)}_i) = \lambda^{(k)}_i \). Since \( \mu^{(k)}_i \) and \( \lambda^{(k)}_i \) are odd, we get \( e(\lambda^{(k)}_i, 1) \neq 0 \). We have that \(|\lambda^{(k)}_i|\) and \(|\mu^{(k)}_i|\) are both 2-disjoint with \( m_1 := \sum_{j \neq i} |\lambda^{(k)}_j| = \sum_{j \neq i} |\mu^{(k)}_j| \subseteq 2 \left\lfloor \frac{n-2^k}{2^k} \right\rfloor \), by Theorem 2.5. Since \( m_1 \subseteq 2 \left\lfloor \frac{n-2^k}{2^k} \right\rfloor \) and \( m_1 \subseteq 2 \left\lfloor \frac{n}{2^k} \right\rfloor \), we get \( m_1 \leq m_2 \). Thus \(|\lambda^{(k)}_i| = (2^d - 1) + m_2\) and \(|\mu^{(k)}_i| = 2^d + m_2\), where \( m_2 = m - m_1 \leq m_2 \).

In particular \( \nu_2(|\lambda^{(k)}_i| + 1) = \nu_2(|\mu^{(k)}_i|) = d \). Then Lemma 3.2 shows that \( \lambda^{(k)}_i \) is \( d \)-good.

Conversely, if \( \lambda^{(k)}_i \) is a \( d \)-good partition for some \( i \in \{0, 1, \ldots, 2^k - 1\} \), then there exists a \( \mu^* \vdash_0 |\lambda^{(k)}_i| + 1 \) such that \( f_0(\mu^*) = \lambda^{(k)}_i \), by Lemma 3.2. We let \( \mu^* \) be the partition where the \( k \)-data \( D^{(k)}_2(\mu) \) and \( D^{(k)}_2(\lambda) \) coincide, except that \( \mu^{(k)}_i = \mu^* \). Since \( \mu \) is odd and \( \lambda^{(k)}_i \) is \( d \)-good,
we know that \(|\lambda_i^{(k)}| = (2^d - 1) + m'\) where \(m' \subseteq m\), and \(|\lambda_j^{(k)}| \subseteq 2m - m'\) for all \(j \neq i\). Hence \(|\mu'| = |\lambda_i^{(k)}| + 1 = 2^d + m'\) is 2-disjoint from all \(|\lambda_j^{(k)}|, j \neq i\). Thus \(\mu\) is an odd partition of \(n\) by Theorem 2.5, and \(f_k(\mu) = \lambda\) by Lemma 2.3 and Remark 2.1.

We conclude that \(e(\lambda, 2^k) = \sum_{\lambda_1^{(k)} \text{ d-good}} e(\lambda_1^{(k)}), 1\). If \(d = 0\) then \(\lfloor \frac{n-2^k}{2^k} \rfloor\) is even. This implies that all \(\lambda_1^{(k)}\) are of even cardinality and thus \(d\)-good. Thus \(e(\lambda_1^{(k)}, 1) = 1\) for all \(i\), and we get \(e(\lambda, 2^k) = 2^k\). If \(d > 0\) there is exactly one \(\lambda_i^{(k)}\) in \(Q_2^{(k)}(\lambda)\) of odd cardinality. Only this \(\lambda_i^{(k)}\) may be \(d\)-good and then \(e(\lambda, 2^k) = e(\lambda_1^{(k)}, 1) = 2\). Otherwise \(e(\lambda, 2^k) = 0\).

**Corollary 3.6.** Let \(n \in \mathbb{N}, k \in \mathbb{N}_0\) be such that \(2^k < n\), and let \(d = v_2(\lfloor \frac{n}{2^k} \rfloor)\). Let \(\lambda \vdash n - 2^k\).

Then \(e(\lambda, 2^k) \neq 0\) if and only if there exists a partition \(\lambda_i^{(k)}\) in the \(k\)th row of \(Q_2(\lambda)\) such that \(|\lambda_i^{(k)}| \equiv 2^d - 1 \mod 2^{d+1}\), and \(C_{2d}(\lambda_i^{(k)})\) is a hook partition. In this case, \(e(\lambda, 2^k) = 2^k\) if \(d = 0\), and \(e(\lambda, 2^k) = 2\) if \(d > 0\).

We are now ready to prove Theorem A. In fact, this is a consequence of Theorem 3.5 and it is stated here as the following corollary.

**Corollary 3.7 (Theorem A).** Let \(n \in \mathbb{N}, k \in \mathbb{N}_0\) be such that \(2^k < n\).

- If \(k = 0\) then \(f_k^n\) is surjective if and only if \(d(n, k) \leq 2\).
- If \(k > 0\) then \(f_k^n\) is surjective if and only if \(d(n, k) \leq 1\).

**Proof.** By Theorem 3.5, \(f_k^n\) is surjective if and only if for all \(\lambda \vdash n - 2^k\) we have that the \(k\)th row of \(Q_2(\lambda)\) contains a \((d(n, k), \text{good})\) partition \(\lambda_1^{(k)}\). By Theorem 2.5 and Definition 3.4, for any \(\lambda \vdash n - 2^k\) we have \(\sum_{j \geq 0} |\lambda_j^{(k)}| = \lfloor \frac{n-2^k}{2^k} \rfloor = (2^{d(n, k)} - 1) + m(n, k)\).

If \(k = 0\) then \(Q_2^{(0)}(\lambda)\) contains only \(\lambda = \lambda_0^{(0)}\). Hence \(f_k^n\) is surjective if and only all odd partitions of \(n - 1\) are \((d(n, 0), \text{good})\). By Lemma 3.3(1), the latter condition holds when \(d = d(n, 0) \leq 2\). On the other hand, if \(d = v_2(n) > 2\), then \(\lambda = (n - 5, 2, 2)\) is an odd partition of \(n - 1\) by Theorem 2.5, but \(C_{2d}(\lambda) = (3, 2, 2)\) is not a hook, and hence \(C_{2d}(\lambda)\) is not a hook. So \(\lambda\) is not \((d, \text{good})\), and thus \(f_k^n\) is not surjective.

Now assume \(k \geq 1\). Then \(Q_2^{(k)}(\lambda)\) contains at least two odd partitions. If \(d(n, k) \geq 2\) then any \((d(n, k), \text{good})\) partition \(\mu\) satisfies \(3 \subseteq 2^{d(n, k)} - 1 \subseteq |\mu|\). Write \(\lfloor \frac{n-2^k}{2^k} \rfloor = 1 + m_1\) where \(m_1\) is even. Applying Remark 2.7, take any \(\lambda \vdash n - 2^k\) such that \(|\lambda_0^{(k)}| = 1\) and \(\lambda_1^{(k)}\) is an odd partition with \(|\lambda_1^{(k)}| = m_1\). Then no partition in \(Q_2^{(k)}(\lambda)\) is \((d(n, k), \text{good})\). Thus \(f_k^n\) is not surjective. On the other hand, if \(d(n, k) = 0\) then \(2^k \subseteq n\) and \(f_k^n\) is surjective [3, Proposition 4.5]. If \(d(n, k) = 1\) then \(\lfloor \frac{n-2^k}{2^k} \rfloor = 1 + m(n, k)\), where \(4 \mid m(n, k)\). Thus any \(Q_2^{(k)}(\lambda)\) contains a partition with odd cardinality; this partition is 1-good, by Lemma 3.3. Again \(f_k^n\) is surjective.

It is an immediate consequence of Theorem 3.5 that \(f_k^n\) is regular on its image for all relevant choices of \(n, k\) such that \(2^k < n\). We have:

**Corollary 3.8.** Let \(n \in \mathbb{N}, k \in \mathbb{N}_0\) be such that \(2^k < n\); set \(d = v_2(\lfloor \frac{n}{2^k} \rfloor)\). Let \(\lambda \vdash n - 2^k\).

Then

\[
e(\lambda, 2^k) = \begin{cases} 2^k & \text{if } d = 0; \\ 2 & \text{if } d > 0, \text{ and the } k\text{th row of } Q_2(\lambda) \text{ contains a } d\text{-good partition}; \\ 0 & \text{otherwise}. \end{cases}
\]
Example 3.9. For an illustration, we consider odd extensions of odd partitions by a 4-hook, i.e., we take $k = 2$ above. For $n > 2^2$ we first compute $d(n, k) = \nu_2\left(\left\lfloor \frac{n}{2^k} \right\rfloor \right)$, and then consider odd partitions of $n - 4$ and their 4-extensions. For $n = 6$, $d(6, 2) = 0$. Thus $e((2), 4) = 4$. The odd 4-extensions of (2) are (6), (3$^2$), (2$^2$, 1$^2$), (2, 1$^4$). For $n = 10$, $d(10, 2) = 1$. In this case, $e(\lambda, 4) = 2$ for all odd partitions $\lambda$ of 6. For instance, the odd 4-extensions of (6) are (10) and (6, 3, 1). For $n = 19$, $d(19, 2) = 2$. Example 2.6 shows that for $\lambda = (5, 4, 2^2, 1^2)$ $\vdash_o 15$ there is no 2-good partition in $Q_2^{(2)}(\lambda)$, hence $e(\lambda, 4) = 0$.

4 Deciding commutativity of the maps $f_k$ and $f_\ell$

Let $n \in \mathbb{N}$, and suppose that $0 \leq k < \ell$ satisfy $2^k + 2^\ell \leq n$. As stated in the introduction, we want to complete the discussion of the commutativity of the maps $f_k$ and $f_\ell$. Since the relevant $n$ will always be apparent for the maps $f_k^n$ in this section, we just write $f_k$.

We write $(n; k, \ell) \in T$ if for all $\lambda \vdash_o n$ we have $f_k f_\ell \lambda = f_\ell f_k \lambda$. Otherwise we write $(n; k, \ell) \in \mathcal{F}$.

In this section we will prove Theorem B, which may be reformulated as follows.

Theorem 4.1. Let $n = 2^t + m$ where $0 \leq m < 2^t$. Suppose that $k$, $\ell$ satisfy $0 \leq k < \ell$ and $2^k + 2^\ell \leq n$. Then with the exception of $(6; 0, 1)$

$$(n; k, \ell) \in \mathcal{F} \text{ if and only if } \ell < t \text{ and } 2^k \leq m.$$

The proof of Theorem 4.1 is based on a series of lemmas. The first lemmas concern two extreme cases, where $f_k$ and $f_\ell$ commute.

In the case $\ell = t$ we have the following result as a reformulation of [3, Proposition 4.3].

Lemma 4.2. Let $n = 2^t + m$ with $0 \leq m < 2^t$. If $2^k \leq m$, then $(n; k, t) \in T$.

It is also known that in the case where $n$ is a power of 2, the maps $f_k$ and $f_\ell$ commute [3, Remark 4.4], and we include a short proof here.

Lemma 4.3. If $n = 2^t$ then $(n; k, \ell) \in T$ for all $k$, $\ell$.

Proof. If $0 \leq b \leq a$ are integers then the binomial coefficient $\binom{a}{b}$ is odd if and only if $b \subseteq_2 a$, by Lucas' theorem. The odd partitions of $2^t$ are exactly the hook partitions $(2^t - b, 1^b)$, $0 \leq b \leq 2^t - 1$, of degree $(2^t - 1)$. Hence for $k \in \{0, 1, \ldots, t - 1\}$ we have

$$f_k \lambda = \begin{cases} (2^t - b - 2^k, 1^b) & \text{if } 2^k \nsubseteq_2 b, \\ (2^t - b, 1^{b - 2^k}) & \text{if } 2^k \nsubseteq_2 b. \end{cases}$$

It follows that for any $k, \ell < t$ and odd partition $\lambda$ of $2^t$, we have $f_\ell f_k \lambda = f_k f_\ell \lambda$.

Lemma 4.4. Let $n = 2^t + m$ with $0 \leq m < 2^t$. Suppose that $k$, $\ell$ satisfy $0 \leq k < \ell$ and $2^k + 2^\ell \leq n$. If $m < 2^k$ then $(n; k, \ell) \in T$.

Proof. We use induction on $k \geq 0$. For $k = 0$ we have $m = 0$ and the claim follows from Lemma 4.3. Suppose that $k \geq 1$ and that the claim has been proved up to $k - 1$. Let $\lambda \vdash_o n$. Odd hooks of length $2^k$ and $2^\ell$ in $\lambda$ correspond to odd hooks of length $2^{k-1}$ and $2^{\ell-1}$ in the 2-quotient $Q_2(\lambda) = (\lambda_o, \lambda_1)$ of $\lambda$. From Theorem 2.5 we deduce that $|\lambda_o|$ and $|\lambda_1|$ are 2-disjoint binary subsums of $\left\lfloor \frac{n}{2^t} \right\rfloor$, so one of them contains $2^{t-1}$, say $|\lambda_0|$; then $|\lambda_1| \leq \left\lfloor \frac{m}{2^t} \right\rfloor < 2^{k-1} < 2^{\ell-1}$. Thus the odd $2^{k-1}$-hook in $Q_2(\lambda)$ has to be in $\lambda_0$. Therefore

$Q_2(f_k(\lambda)) = (f_{k-1}(\lambda_0), \lambda_1)$. 

Applying \( f_\ell \), the odd \( 2^{\ell-1} \)-hook cannot be in \( \lambda_1 \), hence

\[
Q_2(f_\ell f_k(\lambda)) = (f_{\ell-1} f_{k-1}(\lambda_0), \lambda_1)).
\]

In particular, we know that \(|\lambda_0| \geq 2^{\ell-1} + 2^{k-1} \). Also \(|\lambda_0| + |\lambda_1| = \left\lfloor \frac{n}{2} \right\rfloor = 2^{\ell-1} + \left\lfloor \frac{n}{2} \right\rfloor \). We have already seen that \( 2^{\ell-1} \) is the largest binary digit of \(|\lambda_0|\); furthermore \( |\lambda_0| - 2^{\ell-1} \) is a binary subsum of \( \left\lfloor \frac{n}{2} \right\rfloor < 2^{k-1} \). We may therefore apply the inductive hypothesis to \( \lambda_0 \) to get \( f_{\ell-1} f_{k-1}(\lambda_0) = f_{k-1} f_{\ell-1}(\lambda_0) \). This implies that \( Q_2(f_k f_\ell(\lambda)) = Q_2(f_{\ell} f_k(\lambda)) \) and thus \( f_k f_\ell(\lambda) = f_\ell f_k(\lambda). \)

Lemmas 4.2 and 4.4 show that the only if part of the theorem is true. We now turn to the if part. We start by proving the statement for \( k = 0 \) and use this as part of an inductive argument.

**Lemma 4.5.** Let \( n = 2^t + m \) with \( 0 < m < 2^t \). If \( 0 < \ell < t \) then \( (n; 0, \ell) \in \mathcal{F} \), with the exception of \((6; 0, 1)\).

**Proof.** The result is easily checked for \( n \leq 8 \), which includes the exception \((6; 0, 1)\). So we assume that \( t \geq 3 \).

**Case 1:** \( 2^\ell < m \). Then \( n \geq 3 \), since \( \ell > 0 \). Consider the partition \( \lambda = (m, m, 1^a) \vdash n \) where \( a = n - 2m = 2^\ell - m \). The \((1,1)\)-hook length of \( \lambda \) is \( 2^\ell + 1 \). The \((2,1)\)-hook length of \( \lambda \) is \( 2\ell \). Removing the \((2,1)\)-hook hook we get the odd partition \( (m) \), so \( \lambda \) is odd, by Lemma 2.8. We claim that

\[
f_0(\lambda) = (m, m, 1^{a-1}).
\]

Indeed we cannot have \( f_0(\lambda) = (m, m-1, 1^a) \) because this partition does not have a hook of length \( 2^\ell \), and thus it is not odd. Now

\[
f_\ell(f_0(\lambda)) = f_\ell(m, m, 1^{a-1}) = (m, m - 2^\ell, 1^{a-1})
\]

since \( (m, m, 1^{a-1-2^\ell}) \) and \( (m - 1, m - 2^\ell + 1, 1^{a-1}) \) both do not have a hook of length \( 2^\ell \) and thus are not odd (again by Lemma 2.8).

On the other hand,

\[
f_\ell(\lambda) = (m - 1, m - (2^\ell - 1), 1^a).
\]

Indeed, the other candidates for \( f_\ell(\lambda) \), which are \( (m, m - 2^\ell, 1^a) \) and \( (m, m, 1^{a-2^\ell}) \), do not have hooks of length \( 2^\ell \). Then

\[
f_0(f_\ell(\lambda)) = f_0(m - 1, m - (2^\ell - 1), 1^a) = (m - 1, m - 2^\ell, 1^a).
\]

This follows (again) by observing that all the other partitions of \( n - 2^\ell - 1 \) obtained from \( (m - 1, m - (2^\ell - 1), 1^a) \) by removing a node do not have hooks of length \( 2^\ell \). Thus \( f_0(f_\ell(\lambda)) \neq f_\ell(f_0(\lambda)) \).

**Case 2:** \( m < 2^\ell \). Consider the partition \( \lambda = (n - 2^\ell, m + 1, 1^a) \), where \( a = 2^\ell - (m + 1) \). Note that \( n - 2^\ell \geq m + 1 \) since \( \ell < t \) by assumption, and that \( a \geq 0 \). The \((1,1)\)-hook length of \( \lambda \) is \( n - m = 2^t \). Removing this hook we get the odd partition \( (m) \), so \( \lambda \) is odd. The \((2,1)\)-hook length of \( \lambda \) is \( 2^\ell \). Now

\[
f_0(\lambda) = (n - 2^\ell, m, 1^a)
\]

since the other candidates do not have hooks of length \( 2^\ell \). Then

\[
f_\ell(f_0(\lambda)) = f_\ell(n - 2^\ell, m, 1^a) = \mu,
\]
Proof. easy to show that part we use induction on \(2^k\) for showing

Theorem 4.1.

Thus \(f_\ell(f_0(\lambda))\) has at least 2 parts. On the other hand

\[
f_\ell(\lambda) = (n - 2^\ell)
\]

since this odd partition is obtained from the odd partition \(\lambda\) by removing a \(2^\ell\)-hook (the one in \((2,1)\)). It follows that

\[
f_0(f_\ell(\lambda)) = (n - 2^\ell - 1)
\]

and again \(f_0(f_\ell(\lambda)) \neq f_\ell(f_0(\lambda))\).

Case 3: \(n = 2^\ell\). Then \(n = 2^\ell + 2^\ell\). If \(\ell \geq 2\) then choose \(\lambda = (2^\ell, 2^\ell - 1, 1)\). The \((1,2)\)-hook length of \(\lambda\) is \(2^\ell\); thus \(\lambda\) is an odd partition since removing this \(2^\ell\)-hook gives an odd partition \((2^\ell - 2, 1, 1)\) of \(2^\ell\). We have \(f_0(\lambda) = (2^\ell, 2^\ell - 2, 1)\) since the other candidates are not odd. Then

\[
f_\ell(f_0(\lambda)) = (2^\ell - 2^\ell, 2^\ell - 2, 1).
\]

The \((2,1)\)-hook length of \(\lambda\) is \(2^\ell\), so \(f_\ell(\lambda) = (2^\ell)\) and

\[
f_0(f_\ell(\lambda)) = (2^\ell - 1),
\]

showing \(f_0(f_\ell(\lambda)) \neq f_\ell(f_0(\lambda))\).

On the other hand, if \(\ell = 1\) then choose \(\lambda = (2^2 - 2, 2, 2) \vdash_o 2^2 + 2 = n\). Since \(t \geq 3\), it is now easy to show that \(f_1(f_0(\lambda)) = (2^t - 4, 2, 1)\). On the other hand we see that \(f_0(f_1(\lambda))\) is a hook partition of \(2^t - 1 = n - 3\) and therefore is not equal to \(f_1(f_0(\lambda))\).

\[\square\]

Lemma 4.6. If \((n; k, \ell) \in \mathcal{F}\) then also \((2n; k + 1, \ell + 1) \in \mathcal{F}\) and \((2n + 1; k + 1, \ell + 1) \in \mathcal{F}\).

\[\text{Proof.}\] Let the odd partition \(\mu\) of \(n\) satisfy \(f_k f_\ell(\mu) \neq f_\ell f_k(\mu)\). Let \(\lambda\) be a partition of \(2n\) or \(2n + 1\) having 2-quotient \(Q_2(\lambda) = (\mu, (0))\). Then \(\lambda\) is odd, by Theorem 2.5. We have

\[
Q_2(f_{k+1} f_{\ell+1}(\lambda)) = (f_k f_\ell(\mu), (0)) \neq (f_\ell f_k(\mu), (0)) = Q_2(f_{\ell+1} f_{k+1}(\lambda)),
\]

so that \(f_{k+1} f_{\ell+1}(\lambda) \neq f_{\ell+1} f_{k+1}(\lambda)\).

\[\square\]

We are now ready to conclude this section with the proof of Theorem B.

\[\text{Proof of Theorem 4.1.}\] The only if part follows from Lemmas 4.2 and 4.4. To prove the if part we use induction on \(k \geq 0\). If \(k = 0\), then the statement follows from Lemma 4.5. Let \(k > 1\) and suppose that the assertion is true up to and including \(k - 1\). To show that \((n; k, \ell) \in \mathcal{F}\) it suffices to prove \((\lfloor \frac{n}{2} \rfloor; k - 1, \ell - 1) \in \mathcal{F}\), by Lemma 4.6. We are assuming \(n = 2^k + m\), \(0 \leq m < 2^\ell\), \(0 \leq k < \ell \leq t\) and \(2^k + 2^\ell \leq n\). This implies \(\lfloor \frac{n}{2} \rfloor = 2^{t - 1} + \lfloor \frac{m}{2} \rfloor\), \(0 \leq \lfloor \frac{m}{2} \rfloor < 2^{t - 1}\) and \(2^{k - 1} + 2^{\ell - 1} \leq \lfloor \frac{n}{2} \rfloor\). We may apply the inductive hypothesis to get \((\lfloor \frac{n}{2} \rfloor; k - 1, \ell - 1) \in \mathcal{F}\), and then \((n; k, \ell) \in \mathcal{F}\) except when \((\lfloor \frac{n}{2} \rfloor; k - 1, \ell - 1) = (6; 0, 1)\). In that case we are considering \((12; 1, 2)\) or \((13; 1, 2)\) which are both in \(\mathcal{F}\), by direct computation (consider for example \((6, 4, 2) \vdash_o 12\) and \((6, 4, 3) \vdash_o 13\), respectively).

\[\square\]

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