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Self-complementing permutations of $k$-uniform hypergraphs

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A $k$-uniform hypergraph $H = (V; E)$ is said to be self-complementary whenever it is isomorphic with its complement $\overline{H} = (V; \binom{V}{k} - E)$. Every permutation $\sigma$ of the set $V$ such that $\sigma(e)$ is an edge of $\overline{H}$ if and only if $e \in E$ is called self-complementing. 2-self-complementary hypergraphs are exactly self complementary graphs introduced independently by Ringel (1963) and Sachs (1962).

For any positive integer $n$ we denote by $\lambda(n)$ the unique integer such that $n = 2^{\lambda(n)} c$, where $c$ is odd.

In the paper we prove that a permutation $\sigma$ of $[1, n]$ with orbits $O_1, \ldots, O_m$ is a self-complementing permutation of a $k$-uniform hypergraph of order $n$ if and only if there is an integer $l \geq 0$ such that $k = a 2^l + s$, $a$ is odd, $0 \leq s < 2^l$ and the following two conditions hold:

(i) $n = b 2^{l+1} + r$, $r \in \{0, \ldots, 2^l - 1 + s\}$, and
(ii) $\sum_{i: \lambda(O_i) \leq l} |O_i| \leq r$.

For $k = 2$ this result is the very well known characterization of self-complementing permutation of graphs given by Ringel and Sachs.

Keywords: Self-complementing permutations, $k$-uniform hypergraphs

1 Introduction

Let $V$ be a set of $n$ elements. The set of all $k$-subsets of $V$ is denoted by $\binom{V}{k}$. A $k$-uniform hypergraph $H$ consists of a vertex-set $V(H)$ and an edge-set $E(H) \subseteq \binom{V(H)}{k}$. Two $k$-uniform hypergraphs $G$ and $H$ are isomorphic, if there is a bijection $\sigma : V(G) \to V(H)$ such that $e \in E(G)$ if and only if $\{\sigma(x) | x \in e\} \in E(H)$. The complement of a $k$-uniform hypergraph $H$ is the hypergraph $\overline{H}$ such that $V(\overline{H}) = V(H)$ and the edge set of which consists of all $k$-subsets of $V(H)$ not in $E(H)$ (in other words $E(\overline{H}) = \binom{V(H)}{k} - E$). A $k$-uniform hypergraph $H$ is called self-complementary ($s$-$c$ for short) if it is isomorphic with its complement $\overline{H}$. Isomorphism of a $k$-uniform self-complementary hypergraph onto its complement is called self-complementing permutation (or $s$-$c$ permutation).

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The 2-uniform self-complementary hypergraphs are exactly self-complementary graphs. This class of graphs has been independently discovered by Ringel and Sachs who proved the following.

**Theorem 1 (Ringel (Ring63) and Sachs (Sac62))** Let $n$ be a positive integer. A permutation $\sigma$ of $[1,n]$ is a self-complementing permutation of a self-complementary graph of order $n$ if and only if all the orbits of $\sigma$ have their cardinalities congruent to 0 (mod 4) except, possibly, one orbit of cardinality 1.

Observe that by Theorem 1 an s-c graph of order $n$ exists if and only if $n \equiv 0 \text{ or } n \equiv 1 \pmod{4}$ or, equivalently, whenever $\binom{n}{2}$ is even. In (SW) we prove that a similar result is true for $k$-uniform hypergraphs.

**Theorem 2 (SW)** Let $k$ and $n$ be positive integers, $k \leq n$. A $k$-uniform self-complementary hypergraph of order $n$ exists if and only if $\binom{n}{k}$ is even.

A simple criterion for evenness of $\binom{n}{k}$ has been given in (Gla99) (and then rediscovered in (KHRM58)).

**Theorem 3 (Gla99, KHRM58)** Let $k$ and $n$ be positive integers, $k = \sum_{i=0}^{+\infty} c_i 2^i$ and $n = \sum_{i=0}^{+\infty} d_i 2^i$, where $c_i, d_i \in \{0, 1\}$ for every $i$. $\binom{n}{k}$ is even if and only if there is $i_0$ such that $c_{i_0} = 1$ and $d_{i_0} = 0$.

Theorem 3 asserts that $\binom{n}{k}$ is even if and only if $k$ has 1 in a certain binary place while $n$ has 0 in the corresponding binary place. For example, $\binom{27}{13}$ is even since $13 = 1 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0$ and $27 = 1 \cdot 2^4 + 1 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0$ (so we have $c_2 = 1$ and $d_2 = 0$).

Except for Theorem 1 which is a characterization of the self-complementing permutations for graphs, there are already two published results characterizing the permutations of $k$-uniform s-c hypergraphs for $k > 2$. Namely, Kocay in (Koc92) (see also (Pal73)) and Szymański in (Szy05) have characterized the s-c permutations of s-c $k$-uniform hypergraphs for, respectively, $k = 3$ and $k = 4$. This work is a continuation of the work of (SW) and (Woj06). We generalize all the results mentioned above by giving a characterization of the s-c permutations of $k$-uniform hypergraphs for any integers $k$ and $n$.

## 2 Result

Any positive integer $n$ may be written in the form $n = 2^c l$, where $c$ is an odd integer. Moreover, $l$ and $c$ are uniquely determined. We write then $\lambda(n) = l$. Note that in the binary expansion of $n$, $\lambda(n)$ is the index of the first 1–bit. For any set $A$ we shall write $\lambda(A)$ in place of $\lambda(|A|)$, for short.

In the proof of our main result we shall need the following lemma proved in (Woj06).

**Lemma 1** Let $k$, $m$ and $n$ be positive integers, and let $\sigma : V \rightarrow V$ be a permutation of a set $V$, $|V| = n$, with orbits $O_1, \ldots, O_m$. $\sigma$ is a self-complementing permutation of a self-complementary $k$-uniform hypergraph, if and only if, for every $p \in \{1, \ldots, k\}$ and for every decomposition

$$k = k_1 + \ldots + k_p$$

of $k$ ($k_j > 0$ for $j = 1, \ldots, p$), and for every subsequence of orbits

$$O_{i_1}, \ldots, O_{i_p}$$

such that $k_j \leq |O_{i_j}|$ for $j = 1, \ldots, p$, there is a subscript $j_0 \in \{1, \ldots, p\}$ such that

$$\lambda(k_{j_0}) < \lambda(O_{i_{j_0}})$$
Given any integer \( l \geq 0 \). If the binary expansion of \( k \) is \( 1 \)-bit in position \( l \), then \( k \) can be written in the form \( k = a_l 2^l + s_l \), where \( a_l \) is odd and \( 0 \leq s_l < 2^l \).

**Theorem 4** Let \( k \) and \( n \) be integers, \( k \leq n \). A permutation \( \sigma \) of \([1, n]\) with orbits \( O_1, \ldots, O_m \) is a self-complementing permutation of a \( k \)-uniform hypergraph of order \( n \) if and only if there is a nonnegative integer \( l \) such that \( k = a_l 2^l + s_l \), where \( a_l \) is odd and \( 0 \leq s_l < 2^l \), and the following two conditions hold:

(i) \( n = b_l 2^{l+1} + r_l, r_l \in \{0, \ldots, 2^l - 1 + s_l \}, \) and

(ii) \( \sum_{i: \lambda(O_i) \leq l} |O_i| \leq r_l \).

**Proof:**

**Sufficiency.** By contradiction. Let \( n, k, l, a_l, b_l, s_l \) and \( r_l \) be integers verifying the conditions of the theorem, let \( \sigma \) be a permutation of \([1, n]\) with orbits \( O_1, \ldots, O_m \) verifying (ii), and let us suppose that \( \sigma \) is not a s-c permutation of any \( k \)-uniform s-c hypergraph of order \( n \). Then, by Lemma 1, there is a decomposition of \( k = k_1 + \cdots + k_t \) and a subsequence of orbits \( O_{i_1}, \ldots, O_{i_t} \) such that

\[
0 < k_j \leq |O_{i_j}|
\]

(1)

and

\[
\lambda(k_j) \geq \lambda(O_{i_j})
\]

(2)

for \( j = 1, \ldots, t \).

Since \( a_l \) is odd, we have \( k \equiv 2^l + s_l \mod 2^{l+1} \). By \( 2^l \), \( \sum_{j: \lambda(O_{i_j}) > l} k_j \equiv 0 \mod 2^{l+1} \). Therefore

\[
k = \sum_{j=1}^t k_j = \sum_{j: \lambda(O_{i_j}) > l} k_j + \sum_{j: \lambda(O_{i_j}) \leq l} k_j \equiv \sum_{j: \lambda(O_{i_j}) \leq l} k_j \mod 2^{l+1}
\]

Hence, and by (1), (ii) and (ii) we have \( \sum_{j: \lambda(O_{i_j}) \leq l} k_j \leq \sum_{j: \lambda(O_{i_j}) \leq l} |O_{i_j}| \leq 2^l + r_l \), and therefore

\[
2^l + s_l = \sum_{j: \lambda(O_{i_j}) \leq l} k_j \leq \sum_{j: \lambda(O_{i_j}) \leq l} |O_{i_j}| \leq r_l < 2^l + s_l
\]

a contradiction.

**Necessity.** Let \( 1 \leq k \leq n \) and let \( \sigma \) be a permutation of the set \([1, n]\) with orbits \( O_1, \ldots, O_m \). Let us suppose that for every integer \( l \) such that \( k = a_l 2^l + s_l \), where \( a_l \) is odd positive integer, \( 0 \leq s_l < 2^l \), and \( n = b_l 2^{l+1} + r_l, 0 \leq r_l < 2^{l+1} \) we have either

\[
r_l \in \{2^l + s_l, \ldots, 2^{l+1} - 1\}
\]

or

\[
r_l \in \{0, \ldots, 2^l - 1 + s_l\} \quad \text{and} \quad \sum_{i: \lambda(O_i) \leq l} |O_i| > r_l
\]

We shall prove that \( \sigma \) is not a s-c permutation of any s-c \( k \)-uniform hypergraph of order \( n \). For this purpose we shall give two claims.
Claim 1  For every nonnegative integer \( l \) such that \( k = a_l 2^l + s_l \), where \( a_l \) is odd and \( 0 \leq s_l < 2^l \), we have 
\[
\sum_{i: \lambda(O_i) \leq l} |O_i| \geq 2^l + s_l
\]

Proof of Claim 1 Let us write \( \sum_{i: \lambda(O_i) \leq l} |O_i| \) and \( \sum_{i: \lambda(O_i) > l} |O_i| \) in their binary forms:
\[
\sum_{i: \lambda(O_i) \leq l} |O_i| = \sum_{j=0}^{\infty} e_j 2^j,
\]
\[
\sum_{i: \lambda(O_i) > l} |O_i| = \sum_{j=0}^{\infty} f_j 2^j
\]
where \( e_j, f_j \in \{0, 1\} \) for every \( j \). Observe that \( f_j = 0 \) for \( j = 0, \ldots, l \) and therefore
\[
\sum_{j=0}^{l} e_j 2^j = r_l \tag{3}
\]
We shall consider two cases.
Case 1. \( r_l \in \{0, \ldots, 2^l + s_l - 1\} \) and \( \sum_{i: \lambda(O_i) \leq l} |O_i| > r_l \).
We have \( n \geq 2^{l+1} \) (otherwise \( r_l = n = \sum_{i: \lambda(O_i) \leq l} |O_i| \)).
Since \( \sum_{j=0}^{\infty} e_j 2^j > r_l \), and by (3), we obtain \( \sum_{j=0}^{\infty} e_j 2^j \geq 2^{l+1} > 2^l + s_l \).
Case 2. \( r_l \in \{2^l + s_l, \ldots, 2^{l+1} - 1\} \).
We have \( \sum_{i: \lambda(O_i) \leq l} |O_i| = \sum_{j=0}^{\infty} e_j 2^j \geq \sum_{j=0}^{l} e_j 2^j = r_l \geq 2^l + s_l \), and the claim is proved. \( \square \)

Claim 2 Let \( \alpha_1, \ldots, \alpha_q \) and \( \lambda_1, \ldots, \lambda_q \) be integers such that \( 0 < \alpha_i \), \( 0 \leq \lambda_i \leq \lambda(\alpha_i) \) and \( \lambda_i \leq l \) for \( i = 1, \ldots, q \) and \( \sum_{i=1}^{q} \alpha_i \geq 2^l \). Then there are \( \beta_1, \ldots, \beta_q \) such that for every \( i = 1, \ldots, q \)
\[
0 \leq \beta_i \leq \alpha_i
\]
and
\[
either \beta_i = 0 \text{ or } \lambda(\beta_i) \geq \lambda_i
\]
and
\[
\sum_{i=1}^{q} \beta_i = 2^l \tag{6}
\]

Proof of Claim 2 The existence of \( \beta_1, \ldots, \beta_q \) verifying (4)-(6) and \( \sum_{i=1}^{q} \beta_i \leq 2^l \) is very easy. Indeed, it is immediate that \( \beta_1 = 2^{\lambda_1}, \beta_2 = \ldots, \beta_q = 0 \) is a sequence with the desired properties.
So let us suppose that \( \beta_1, \ldots, \beta_q \) is a sequence verifying (4)-(6) and \( \sum_{i=1}^{q} \beta_i \leq 2^l \) such that \( \sum_{i=1}^{q} \beta_i \) is maximal. If \( \sum_{i=1}^{q} \beta_i = 2^l \) then the proof is complete. So let us suppose that \( \sum_{i=1}^{q} \beta_i < 2^l \). Then there is \( i_0 \in \{1, \ldots, q\} \) such that \( \beta_{i_0} < \alpha_{i_0} \). Observe that \( \beta_{i_0} + 2^{\lambda_{i_0}} \leq \alpha_{i_0} \). The sequence \( \beta_1, \ldots, \beta_q \) defined by \( \beta_{i_0} = \beta_{i_0} + 2^{\lambda_{i_0}} \) and \( \beta_i = \beta_i \) for \( i \neq i_0 \) also verifies (4)-(6) and \( \sum_{i=1}^{q} \beta_i \leq 2^l \), which contradicts the maximality of the sum \( \sum_{i=1}^{q} \beta_i \), and the claim is proved. \( \square \)

We shall use our claims to construct a decomposition of \( k \) in the form \( k = k_1 + \ldots + k_m \) such that
(1) \(k_1, \ldots, k_m\) are nonnegative integers,
(2) \(k_i \leq |O_i|\) for \(i = 1, \ldots, m\), and
(3) \(\lambda(k_i) \geq \lambda(O_i)\) whenever \(k_i > 0\)

By Lemma 1, this will imply that \(\sigma\) is not a s-c permutation of any \(k\)-uniform s-c hypergraph.

Let us write \(k\) in its binary form:

\[ k = 2^{l_t} + 2^{l_{t-1}} + \ldots + 2^{l_1} + 2^{l_0} \]

where \(l_0 < l_1 < \ldots < l_t\).

By Claim 1, \(\sum_{i:|O_i| \leq l_0} |O_i| \geq 2^{l_0}\). Hence, and by Claim 2, there are nonnegative integers \(k_1^{(0)}, k_2^{(0)}, \ldots, k_m^{(0)}\) such that \(k_i^{(0)} = 0\) for \(i\) such that \(\lambda(O_i) > l_0\) and

\[ k_i^{(0)} \leq |O_i| \text{ for } i = 1, \ldots, m \]

\[ \lambda(k_i^{(0)}) \geq \lambda(O_i) \text{ whenever } k_i^{(0)} > 0 \]

and

\[ \sum_{i=1}^{m} k_i^{(0)} = 2^{l_0} \]

Note that, for \(i = 1, \ldots, m\), we have \(\lambda(|O_i| - k_i^{(0)}) \geq \lambda(O_i)\).

Let us suppose that we have already constructed \(k_1^{(j)}, \ldots, k_m^{(j)}, (j \leq t)\), such that \(k_i^{(j)} = 0\) for \(i\) such that \(\lambda(O_i) > l_t\) and

\[ k_i^{(j)} \leq |O_i| \text{ for } i = 1, \ldots, m \]

\[ \lambda(k_i^{(j)}) \geq \lambda(O_i) \text{ whenever } k_i^{(j)} > 0 \]

\[ \sum_{i=0}^{m} k_i^{(j)} = 2^{l_j} + 2^{l_{j-1}} + \ldots + 2^{l_0} \]

and

\[ \lambda(|O_i| - k_i^{(j)}) \geq \lambda(O_i) \]

If \(j = t\), then we have already found a desired decomposition of \(k\). If \(j < t\), then, by Claim 1, we have \(\sum_{i:|O_i| \leq l_{j+1}} |O_i| - k_i^{(j)} \geq 2^{l_{j+1}}\).

\(\lambda(|O_i| - k_i^{(j)}) \geq \lambda(O_i)\) for every \(i \in \{1, \ldots, m\}\) such that \(|O_i| - k_i^{(j)} > 0\). Hence, and by Claim 2, there are \(\beta_1, \ldots, \beta_m\) such that \(\beta_i = 0\) for \(i\) such that \(\lambda(O_i) > l_{j+1}\) and

\[ 0 \leq \beta_i \leq |O_i| - k_i^{(j)} \text{ for } i = 1, \ldots, m \]

\[ \lambda(O_i) \leq \lambda(\beta_i) \text{ for } i = 1, \ldots, m \text{ whenever } \beta_i \neq 0 \]

\[ \sum_{i=1}^{m} \beta_i = 2^{l_{j+1}} \]
Thus we may define for every $i = 1, \ldots, m$

$$k_i^{(j+1)} = k_i^{(j)} + \beta_i$$

to obtain the sequence $(k_1^{(j+1)}, \ldots, k_m^{(j+1)})$ verifying for every $i \in \{1, \ldots, m\}$

$$k_i^{(j+1)} = 0 \text{ for } i \text{ such that } \lambda(O_i) > l_{j+1}$$

$$k_i^{(j+1)} \leq |O_i|$$

$$\lambda(k_i^{(j+1)}) \geq \lambda(O_i) \text{ whenever } k_i^{(j+1)} > 0$$

and

$$\sum_{i=1}^{m} k_i^{(j+1)} = 2^{l_{j+1}} + 2^{l_j} + \ldots + 2^{l_0}$$

It is clear that $k = \sum_{i=1}^{m} k_i^{(t)}$ and the proof of Theorem 4 is complete.

Theorem 4 implies very easily the following theorem first proved by Kocay.

**Corollary 1 (Kocay (Koc92))** $\sigma$ is a self-complementing permutation of a self-complementary 3-uniform hypergraph if and only if either all the orbits of $\sigma$ have even cardinalities, or else, it has 1 or 2 fixed points and the all remaining orbits of $\sigma$ have their cardinalities being multiples of 4.

For $k = 2^l$ Theorem 4 may be written as follows.

**Corollary 2** Let $l$ and $n$ be nonnegative integers, $2^l < n$, and let $0 \leq r < 2^{l+1}$ be such that $n \equiv r \pmod{2^{l+1}}$. A permutation $\sigma$ of $[1, n]$ with orbits $O_1, \ldots, O_m$ is a self-complementing permutation of a $2^l$-uniform self-complementary hypergraph if and only if

(i) $r \in \{0, \ldots, 2^l - 1\}$ and

(ii) $\sum_{r: \lambda(O_i) \leq l} |O_i| \leq r$.

Theorem 2 for $l = 1$ (i.e. for graphs) is exactly Theorem 1 and for $l = 2$ the following theorem proved by Szymański in [Szy05].

**Corollary 3** A permutation $\sigma$ is self-complementing permutation of a 4-uniform hypergraph of order $n$ if and only if $n \equiv r \pmod{8}$ with $r = 0, 1, 2$ or $3$, and the sum of the cardinalities of orbits which are not multiples of 8 is at most 3.

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