

**THE SIZE OF MINIMUM 3-TREES:
CASES 0 AND 1 MOD 12**

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Abstract

A 3-uniform hypergraph is called a minimum 3-tree, if for any 3-coloring of its vertex set there is a heterochromatic triple and the hypergraph has the minimum possible number of triples. There is a conjecture that the number of triples in such 3-tree is $\lceil \frac{n(n-2)}{3} \rceil$ for any number of vertices n . Here we give a proof of this conjecture for any $n \equiv 0, 1 \pmod{12}$.

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1. INTRODUCTION

A 3-graph is an ordered pair of sets $G = (V, \Delta)$. The elements of V are called *vertices*. The elements of Δ are subsets of vertices of cardinality 3 and are called *triples*. Given a 3-graph $G = (V, \Delta)$ and a vertex v the trace

$Tr_G(v)$ of v in G is the graph with vertex set $V \setminus \{v\}$, and a pair $\{x, y\}$ is an edge of $Tr_G(v)$ if and only if $\{v, x, y\}$ is a triple of G .

A *3-coloring* of a 3-graph is a surjective map from the vertex set onto a set of three elements. A 3-graph is said to be *tight* (see [1]) if any 3-coloring has a heterochromatic triple i.e., a triple whose vertices are colored differently. A tight 3-graph is called a *3-tree* if whenever we delete a triple from it we obtain an untight 3-graph. Different 3-trees on n vertices may have a different number of triples. From the results of [4], we know that the maximum number of triples in any 3-tree is $\binom{n-1}{2}$. It is not difficult to show that the minimum number of triples in such a 3-tree is not less than $\lceil \frac{n(n-2)}{3} \rceil$. In [1] it was proved that this bound is sharp for any n of the form $\frac{p-1}{2}$ where p is a prime number, and it was conjectured that the bound is sharp for any n . In [2] the case when $n \equiv 3, 4 \pmod{6}$ was solved and in [3] a full proof for the case $n \equiv 2 \pmod{3}$ is given.

Here we give the proof of the cases $n \equiv 0, 1 \pmod{12}$. The case $1 \pmod{12}$ is solved via a generalization of a construction from [2].

2. THE CASE $0 \pmod{12}$

In order to prove the conjecture for any n it is sufficient to construct a 3-tree with $\lceil \frac{n(n-2)}{3} \rceil$ triples. In this section we deal only with the case $n \equiv 0 \pmod{12}$.

Let us consider the cyclic group $\mathbb{Z}_n = \{0, 1, \dots, n-1\}$, its elements are the vertices of the 3-graph H_n defined below.

Of course, we know how to add vertices. If $e = \{x_1, x_2, x_3\}$ is a triple and y is a vertex, then $e+y = \{x_1+y, x_2+y, x_3+y\}$. If F is any set of triples and S any set of vertices then $F+S = \{f+s \mid f \in F, s \in S\}$. It is important to observe that all operations must be interpreted in the appropriate cyclic group.

Denote by $\mathbb{A}_n = \{1, \dots, \frac{n}{6}\} \subset \mathbb{Z}_n$ and $\mathbb{B}_n = \{1, \dots, \frac{n}{12}\} \subset \mathbb{A}_n$. For $a \in \mathbb{A}_n$ and $b \in \mathbb{B}_n$, let us consider the following triples:

$$\begin{aligned}\varepsilon_a &= \{0, 2\frac{n}{3}, 2a\}, \\ \zeta_b &= \{0, 2, 3-4b\}, \\ \eta_b &= \{0, 2\frac{n}{3} + 2b, 4b-1\}.\end{aligned}$$

Those triples generate the set of triples of the 3-graph H_n i.e., any triple will be of the form $\varepsilon_a + y$ or $\zeta_b + y$ or $\eta_b + y$ where $y \in \mathbb{Z}_n$. Formally, denote

$$H_n = (\mathbb{Z}_n, (\{\varepsilon_a \mid a \in \mathbb{A}_n\} \cup \{\zeta_b, \eta_b \mid b \in \mathbb{B}_n\}) + \mathbb{Z}_n).$$

Our purpose is to show that H_n is a 3-tree with $\frac{n(n-2)}{3}$ triples.

Proposition 1. H_n has $\frac{n(n-2)}{3}$ triples.

Proof. There are $n(\frac{n}{6} - 1) + \frac{n}{3}$ triples generated by ε_a . The number of triples generated by ζ_b and η_b is $\frac{n^2}{6}$. Those triples are all different and a straightforward calculation gives the result. ■

Let us construct an auxiliary hypergraph. For this, let $m \equiv 0 \pmod{3}$ and denote $\alpha_a = \{0, 2\frac{m}{3}, a\}$.

The hypergraph G_m is by definition $(\mathbb{Z}_m, \{\alpha_a \mid a \in \{1, \dots, \frac{m}{3}\}\} + \mathbb{Z}_m)$.

Observe that the hypergraph generated by the set of even vertices in H_n contains a copy of $G_{n/2}$ and also the hypergraph generated by the set of odd ones by the automorphism $x \mapsto x + 1$ of H_n .

Lemma 2. Let f be a non heterochromatic 3-coloring of G_m . Then, all the cosets of \mathbb{Z}_m by the subgroup $\langle \frac{m}{3} \rangle \cong \mathbb{Z}_3$ are monochromatic.

Proof. Denote $t = \frac{m}{3}$. Let f be a red-blue-yellow 3-coloring for which the lemma is false. Let $y \in \mathbb{Z}_m$, observe that for the 3-coloring $f + y : a \mapsto f(a + y)$ the lemma is also false. So we can suppose that $|f(\alpha_t)| = 2$, and $f(0) = f(-t) = R$ and $f(t) = B$. So for any $a \in \{1, \dots, t\}$ we have

$$\left. \begin{array}{l} \alpha_a + t = \{t, 0, a + t\} \in G_m \\ \text{and } f(0) = R, f(t) = B. \end{array} \right\} \Rightarrow f(a + t) \neq Y,$$

$$\left. \begin{array}{l} \alpha_a - t = \{-t, t, a - t\} \in G_m \\ \text{and } f(-t) = R, f(t) = B. \end{array} \right\} \Rightarrow f(a - t) \neq Y.$$

Therefore, since any 3-coloring is a surjective map there must be an $x \in \{1, \dots, t-1\}$ such that $f(x) = Y$. In this case we have

$$\left. \begin{array}{l} \alpha_{t-x} + x = \{x, x - t, t\}, \alpha_x - t = \{-t, t, x - t\} \in G_m \\ \text{and } f(-t) = R, f(t) = B, f(x) = Y. \end{array} \right\} \Rightarrow f(x - t) = B,$$

$$\left. \begin{array}{l} \alpha_{t-x} + x + t = \{x + t, x, -t\}, \alpha_x + t = \{t, 0, x + t\} \in G_m \\ \text{and } f(-t) = f(0) = R, f(t) = B, f(x) = Y. \end{array} \right\} \Rightarrow f(x + t) = R$$

and this is a contradiction because $\alpha_t + x = \{x, x - t, x + t\} \in G_m$. \blacksquare

Of course, the lemma is equivalent to the fact that any non heterochromatic 3-coloring of G_m factorizes through a 3-coloring of the quotient hypergraph $G_m/\langle \frac{m}{3} \rangle$, i.e., the 3-graph whose vertices are the cosets modulo $\langle \frac{m}{3} \rangle$ and the triples are the images of the triples in G_m by the natural map (see [1] for a more formal definition).

Let us prove a key property of the hypergraph H_n .

Lemma 3. *If f is a non heterochromatic 3-coloring of H_n , then f is surjective in the set of odd vertices or is surjective in the set of even vertices.*

Proof. For two vertices $x, y \in \mathbb{Z}_n$ define the distance between them as the minimal natural number d such that $(d \bmod n) + x = y$ or $(d \bmod n) + y = x$.

Let f be a non heterochromatic 3-coloring of H_n . Both cosets, $\langle 2 \rangle$ and $\langle 2 \rangle + 1$ can not be monochromatic.

Suppose that $f(\langle 2 \rangle + 1) = Y$, then $f(\langle 2 \rangle) = \{R, B\}$ and since $x \mapsto x + 2$ is an automorphism of H_n we also may assume that $f(0) = R$ and $f(2) = B$. Therefore the triple $\zeta_1 = \{0, 2, -1\}$ contradicts the fact that f is non heterochromatic. So, both cosets are bichromatic.

Let Y be the common color to both cosets. Let x and y be vertices such that $f(\{x, y\}) = \{R, B\}$ and the distance between x and y is minimal. Since $x \mapsto x + 1$ is an automorphism of H_n we may assume that $y = 0$, $f(0) = R$ and $f(x) = B$. Therefore, $f(\langle 2 \rangle) = \{R, Y\}$, $f(\langle 2 \rangle + 1) = \{B, Y\}$ and $x \in \{\frac{n}{2} + 1, \frac{n}{2} + 3, \dots, -1\}$. Of course, by the minimality of the distance between x and y , for all $z \in \{x + 1, x + 2, \dots, -1\}$ we have $f(z) = Y$.

For $x \in \{\frac{n}{2} + 1, \frac{n}{2} + 3, \dots, 2\frac{n}{3} - 1\}$, let d be the solution in \mathbb{B}_n of $2\frac{n}{3} - 2d + 1 = x$. In this case the triple $\eta_d + 1 - 4d = \{1 - 4d, 0, x\} \in H_n$ is heterochromatic and this is a contradiction.

On the other hand, let $x \in \{2\frac{n}{3} + 1, 2\frac{n}{3} + 3, \dots, -1\}$.

If $x \equiv 1 \pmod{4}$ then let us consider the solution d in \mathbb{B}_n of $1 - 4d = x$. In this case, the triple $\zeta_d - 2 = \{-2, 0, x\} \in H_n$ gives a contradiction.

If $x \equiv 3 \pmod{4}$ then let d be the solution in \mathbb{B}_n of $3 - 4d = x$. In this case we have

$$\left. \begin{array}{l} \eta_d + x = \{x, x + 2\frac{n}{3} + 2d, 2\} \in H_n, \\ f(x) = B, f(x + 2\frac{n}{3} + 2d) = Y, f(2) \neq B. \end{array} \right\} \Rightarrow f(2) = Y$$

and the triple $\zeta_d = \{0, 2, x\} \in H_n$ is heterochromatic, which is impossible. \blacksquare

Lemma 4. *If f is a non heterochromatic 3-coloring of H_n , then f is surjective in the set of odd vertices and is also surjective in the set of even vertices.*

Proof. Let f be a non heterochromatic 3-coloring of H_n then by the preceding lemma we may suppose that $f(\langle 2 \rangle) = \{R, B, Y\}$ and $R \notin f(\langle 2 \rangle + 1)$.

Since the hypergraph generated by $\langle 2 \rangle$ is isomorphic to $G_{n/2}$, hence by Lemma 2, for all $\alpha \in \langle 2 \rangle$ the coset $\langle \frac{n}{3} \rangle + \alpha$ must be monochromatic. So, we can suppose that $f(\langle \frac{n}{3} \rangle) = R$ and $f(\langle \frac{n}{3} \rangle + 2) = B$.

For a better understanding, we urge the reader to remember (see the beginning of Section 2) that we can add a set of vertices to a triple thus obtaining in this way a set of triples.

For all $b \in \mathbb{B}_n$ we have that

$$\left. \begin{array}{l} \zeta_b + \langle \frac{n}{3} \rangle = \{0, 2, 3 - 4b\} + \langle \frac{n}{3} \rangle, \\ f(\langle \frac{n}{3} \rangle) = R, f(\langle \frac{n}{3} \rangle + 2) = B \\ \text{and } R \notin f(\langle \frac{n}{3} \rangle + 3 - 4b). \end{array} \right\} \Rightarrow f(\langle \frac{n}{3} \rangle + 3 - 4b) = B.$$

Observe that

$$\bigcup_{b \in \mathbb{B}_n} (\langle \frac{n}{3} \rangle + 3 - 4b) = \bigcup_{b \in \mathbb{B}_n} (\langle \frac{n}{3} \rangle + 4b - 1)$$

and therefore for any $b \in \mathbb{B}_n$, $f(\langle \frac{n}{3} \rangle + 4b - 1) = B$ holds.

On the other hand

$$\left. \begin{array}{l} \zeta_b + 4b - 3 + \langle \frac{n}{3} \rangle = \{4b - 3, 4b - 1, 0\} + \langle \frac{n}{3} \rangle, \\ f(\langle \frac{n}{3} \rangle) = R, f(\langle \frac{n}{3} \rangle + 4b - 1) = B \\ \text{and } R \notin f(\langle \frac{n}{3} \rangle + 4b - 3). \end{array} \right\} \Rightarrow f(\langle \frac{n}{3} \rangle + 4b - 3) = B.$$

Since every odd vertex is either in some coset of the form $\langle \frac{n}{3} \rangle + 4b - 1$ or in some coset of the form $\langle \frac{n}{3} \rangle + 4b - 3$, hence $f(\langle 2 \rangle + 1) = B$.

Let $x \in \langle 2 \rangle$ a vertex colored yellow. Recall that $f(\langle \frac{n}{3} \rangle + x) = Y$ so we can suppose that $x \in \{2, 4, \dots, \frac{n}{3} - 2\} = 2\mathbb{B}_n \cup (\frac{n}{3} - 2\mathbb{B}_n)$. If $x = 2b$, $b \in \mathbb{B}_n$ we have the heterochromatic triple $\eta_b = \{0, x - \frac{n}{3}, 4b - 1\} \in H_n$. In any other case, $x = \frac{n}{3} - 2b$, $b \in \mathbb{B}_n$ and the triple $\eta_b + x = \{x, 0, \frac{n}{3} + 2b - 1\} \in H_n$ is heterochromatic and this is a contradiction. ■

Lemma 5. *If f is a non heterochromatic 3-coloring of H_n , then all the cosets of \mathbb{Z}_n by the subgroup $\langle \frac{n}{3} \rangle \cong \mathbb{Z}_3$ are monochromatic.*

Proof. Let f be a non heterochromatic 3-coloring of H_n , then by Lemma 4 f is surjective in the set of odd vertices and in the set of even vertices. Both sets of vertices induce hypergraphs that are isomorphic to $G_{n/2}$. By Lemma 2 the cosets mod $(n/6)$ in $G_{n/2}$ are monochromatic but these cosets are precisely the cosets mod $(n/3)$ in \mathbb{Z}_n (by the two isomorphisms). ■

Lemma 6. *H_n is tight if and only if $H_n / \langle \frac{n}{3} \rangle$ is tight.*

Proof. Any non heterochromatic 3-coloring f' of $H_n / \langle \frac{n}{3} \rangle$ lifts to a non heterochromatic 3-coloring f of H_n . On the other hand (by the preceding lemma) any non heterochromatic 3-coloring f of H_n factorizes (i.e., $f = f' \circ \text{nat}$) through a non heterochromatic 3-coloring f' of $H_n / \langle \frac{n}{3} \rangle$. ■

Theorem 7. *H_n is tight.*

Proof. Denote $\widehat{H}_n = H_n / \langle \frac{n}{3} \rangle$. Let f' be a non heterochromatic 3-coloring of H_n . As in the preceding lemma the map f' factorizes through a non heterochromatic 3-coloring f of \widehat{H}_n , moreover by Lemma 4 f' (and so f) is surjective in the set of odd and in the set of even vertices. Denote by $t = \frac{n}{3}$ and recall that $f : \mathbb{Z}_n / \langle \frac{n}{3} \rangle \cong \mathbb{Z}_t \rightarrow \{R, B, Y\}$ is a non heterochromatic red-blue-yellow 3-coloring of \widehat{H}_n .

First we shall prove that there is an x such that $f(x) = f(x+1)$. Suppose not. If there is no y such that $f(y) = f(y+2)$ then, $t \equiv 0 \pmod{3}$, the cosets $\langle 3 \rangle$, $\langle 3 \rangle + 1$ and $\langle 3 \rangle + 2$ are monochromatic and the triple $\zeta_{\frac{t}{4}-1} \pmod{t} = \{0, 2, 7\} \in \widehat{H}_n$ gives a contradiction. So, there exists $y \in \mathbb{Z}_t$ such that $f(y) = f(y+2) = R$. If $f(y+1) = R$ or $f(y+3) = R$ then we are done. Let $f(y+1) = B$. The triple $(\zeta_1 \pmod{t}) + y + 1 = \{y+1, y+3, y\} \in \widehat{H}_n$ shows that $f(y+3) = B$. Taking as a new y the vertex $y+1$ and repeating

this argument the needed number of times we conclude that there is not a yellow vertex which is a contradiction.

Therefore we can suppose that $f(0) = R$, $f(1) = f(2) = B$. For all $b \in \mathbb{B}_n = \{1, \dots, \frac{n}{12}\} \subset \mathbb{Z}_n$ denote $b' = -4b \bmod t \in \mathbb{Z}_t$. We have that

$$\left. \begin{array}{l} \zeta_b \bmod t = \{0, 2, b' + 3\} \in \widehat{H}_n, \\ f(0) = R, f(2) = B. \end{array} \right\} \Rightarrow f(b' + 3) \neq Y.$$

Observe that $\{b' : b \in \mathbb{B}_n\} = \langle 4 \rangle \subset \mathbb{Z}_t$. Since f is surjective in the set of odd vertices there must be a vertex $c' \in \langle 4 \rangle$ such that $f(c' + 1) = Y$ and $c' \neq 0$. Let c be the element in \mathbb{B}_n such that $c' = -4c \bmod t$. We have that

$$\left. \begin{array}{l} (\zeta_{\frac{n}{12}} \bmod t) - 2 = \{-2, 0, 1\} \in \widehat{H}_n, \\ (\zeta_c \bmod t) - 2 = \{-2, 0, c' + 1\} \in \widehat{H}_n \\ \text{and } f(0) = R, f(1) = B, f(c' + 1) = Y. \end{array} \right\} \Rightarrow f(-2) = R.$$

Now, let d be the element in \mathbb{B}_n such that $c' + 4 = 4d \bmod t$. We have that

$$\left. \begin{array}{l} (\zeta_d \bmod t) + c' + 1 = \{c' + 1, c' + 3, 0\} \in \widehat{H}_n, \\ \zeta_c \bmod t = \{0, 2, c' + 3\} \in \widehat{H}_n \\ \text{and } f(0) = R, f(2) = B, f(c' + 1) = Y. \end{array} \right\} \Rightarrow f(c' + 3) = R.$$

Since f is surjective in the set of even vertices there must be a vertex $x \in \langle 2 \rangle$ such that $f(x) = B$. If $x \in \langle 4 \rangle$ then $b' = x - c' - 4 \in \langle 4 \rangle$. In this case the triple

$$(\zeta_b \bmod t) + c' + 1 = \{c' + 1, c' + 3, x\} \in \widehat{H}_n$$

gives a contradiction. If $x \notin \langle 4 \rangle$ then, $b' = x - c' - 2 \in \langle 4 \rangle$ and we have

$$\left. \begin{array}{l} (\zeta_b \bmod t) + c' - 1 = \{c' - 1, c' + 1, x\} \in \widehat{H}_n, \\ f(c' - 1) \neq Y, f(c' + 1) = Y, f(x) = B. \end{array} \right\} \Rightarrow f(c' - 1) = B.$$

Therefore, the triple $(\zeta_d \bmod t) + c' - 1 = \{c' - 1, c' + 1, -2\} \in \widehat{H}_n$ is heterochromatic, which is impossible. \blacksquare

3. THE CASE 1 mod 12

When $n \equiv 1 \pmod{3}$ the bound for the number of triples in a tight 3-graph is $\frac{n(n-2)+1}{3}$. This bound can be reached in a 3-graph in which the trace of one

vertex is a cycle and the trace of any other vertex is a tree. Such 3-graph will be called an *almost 3-tree*.

Let M be a 3-tree with n vertices with $n \equiv 0 \pmod{3}$ and suppose that M has a set T of $\frac{n}{3}$ disjoint triples. Let C be a cycle passing through every vertex of M . Define the 3-graph \widetilde{M} obtained from M by the following procedure:

- add a new vertex $*$,
- add the triples $\{*, v, w\}$ where $\{v, w\}$ is an edge of C ,
- delete all the triples of T .

It is easy to see, that if all the traces of vertices in \widetilde{M} are connected then \widetilde{M} is an almost 3-tree. In particular, if we can prove that \widetilde{M} is tight then we have a proof of the conjecture on the minimum size of tight 3-graph for the case $n + 1$.

In this section we construct a 3-graph \widetilde{H}_n which is an almost 3-tree and prove that it is tight.

Recall our definition of H_n from Section 1

$$H_n = (\mathbb{Z}_n, (\{\varepsilon_a \mid a \in \mathbb{A}_n\} \cup \{\zeta_b, \eta_b \mid b \in \mathbb{B}_n\}) + \mathbb{Z}_n),$$

where

$$\begin{aligned} \varepsilon_a &= \{0, 2\frac{n}{3}, 2a\}, \quad \zeta_b = \{0, 2, 3 - 4b\}, \quad \eta_b = \{0, 2\frac{n}{3} + 2b, 4b - 1\}, \\ \mathbb{A}_n &= \{1, \dots, \frac{n}{6}\} \subset \mathbb{Z}_n, \quad \mathbb{B}_n = \{1, \dots, \frac{n}{12}\} \subset \mathbb{A}_n \end{aligned}$$

and $n \equiv 0 \pmod{12}$.

Let T be the set of triples $\{\varepsilon_{n/6} + \mathbb{Z}_n\}$ and C be the cycle $\{\{x, x + 1\} \mid x \in \mathbb{Z}_n\}$. Let \widetilde{H}_n be the 3-graph obtained as above, i.e.,

$$\widetilde{H}_n = (\mathbb{Z}_n \cup \{*\}, (\{\varepsilon_a \mid a \in \mathbb{A}_n \setminus \{\frac{n}{6}\}\} \cup \{\zeta_b, \eta_b \mid b \in \mathbb{B}_n\} \cup \{*, 0, 1\}) + \mathbb{Z}_n)$$

where, by definition, $* + x = *$ for all $x \in \mathbb{Z}_n$.

Theorem 8. \widetilde{H}_n is tight.

Proof. The proof bellow is not valid for the case $n = 12$. However, for that case we can prove that \widetilde{H}_{12} is tight checking all possible colorings (the number of colorings can be reduced using the symmetries of \widetilde{H}_{12} and the fact that H_{12} is tight).

So, let $s = n/12$, $s \geq 2$ and let f be a non heterochromatic 3-coloring of \widetilde{H}_n .

There must be a vertex x in \mathbb{Z}_n such that $f(x) = f(*)$ for if this is not the case, then there are two consecutive vertices $y, y + 1$ such that $f(y) \neq f(y + 1)$ and therefore the triple $\{*, y, y + 1\}$ gives a contradiction.

Then f is surjective in \mathbb{Z}_n . By Theorem 7 there must be an heterochromatic triple $\varepsilon_{2s} + x \in H_n$. Since $x \mapsto x + 1$ is an automorphism of H_n and \tilde{H}_n , we can suppose that $x = 0$. Let $f(0) = R$, $f(4s) = B$ and $f(8s) = Y$.

We divide the proof in two cases when $f(0) = f(2)$ and otherwise.

If $f(0) = f(2) = R$ then

$$\left. \begin{array}{l} \varepsilon_1 + 8s = \{8s, 4s, 8s + 2\}, \\ \varepsilon_{2s-1} + 2 = \{2, 8s + 2, 4s\}, \\ f(2) = R, f(4s) = B, f(8s) = Y. \end{array} \right\} \Rightarrow f(8s + 2) = B,$$

$$\left. \begin{array}{l} \varepsilon_s = \{0, 8s, 2s\}, \varepsilon_{s-1} + 2 = \{2, 8s + 2, 2s\}, \\ f(0) = R, f(2) = R, f(8s) = Y, f(8s + 2) = B. \end{array} \right\} \Rightarrow f(2s) = R,$$

$$\left. \begin{array}{l} \zeta_1 + 8s = \{8s, 8s + 2, 8s - 1\}, \\ \eta_s + 4s = \{4s, 8s - 1, 2s\}, \\ f(2s) = R, f(4s) = B, f(8s) = Y, f(8s + 2) = B. \end{array} \right\} \Rightarrow f(8s - 1) = B,$$

$$\left. \begin{array}{l} \varepsilon_1 + 4s = \{4s, 0, 4s + 2\}, \\ \varepsilon_{2s-1} + 4s + 2 = \{4s + 2, 2, 8s\}, \\ f(0) = R, f(2) = R, f(4s) = B, f(8s) = Y. \end{array} \right\} \Rightarrow f(4s + 2) = R,$$

$$\left. \begin{array}{l} \varepsilon_{2s-2} = \{0, 8s, 4s - 4\}, \\ \varepsilon_{2s-3} + 2 = \{2, 8s + 2, 4s - 4\}, \\ f(0) = R, f(2) = R, f(8s) = Y, f(8s + 2) = B. \end{array} \right\} \Rightarrow f(4s - 4) = R,$$

$$\left. \begin{array}{l} \varepsilon_{2s-2} + 4s = \{4s, 0, 8s - 4\}, \\ \varepsilon_2 + 8s - 4 = \{8s - 4, 4s - 4, 8s\}, \\ f(0) = R, f(4s - 4) = R, f(4s) = B, f(8s) = Y. \end{array} \right\} \Rightarrow f(8s - 4) = R$$

and

$$\left. \begin{array}{l} \eta_1 + 8s = \{8s, 8s + 3, 4s + 2\}, \\ \eta_2 + 8s - 4 = \{8s - 4, 8s + 3, 4s\}, \\ f(4s) = B, f(4s + 2) = R, f(8s - 4) = R, f(8s) = Y. \end{array} \right\} \Rightarrow f(8s + 3) = R.$$

Moreover, if $f(8s + 1) = R$ then no matter the color of $*$ is, some of the triples $\{*, 8s - 1, 8s\}$, $\{*, 8s, 8s + 1\}$ or $\{*, 8s + 1, 8s + 2\}$ gives a contradiction. Hence

$$\left. \begin{array}{l} \zeta_s + 8s - 1 = \{8s - 1, 8s + 1, 4s + 2\} \in \widetilde{H}_n, \\ f(4s + 2) = R, f(8s - 1) = B, f(8s + 1) \neq R. \end{array} \right\} \Rightarrow f(8s + 1) = B$$

and the triple $\zeta_1 + 8s + 1 = \{8s + 1, 8s + 3, 8s\}$ gives a contradiction.

Now, suppose that $f(0) \neq f(2)$. If $f(4s) = f(4s + 2)$ then using the automorphism $x \mapsto x - 4s$ we reduce the proof to the first case. By the same argument $f(8s) \neq f(8s + 2)$. Moreover,

$$\left. \begin{array}{l} \varepsilon_1 = \{0, 8s, 2\} \in \widetilde{H}_n, \\ f(0) = R, f(8s) = Y, f(2) \neq R. \end{array} \right\} \Rightarrow f(2) = Y,$$

$$\left. \begin{array}{l} \varepsilon_1 + 4s = \{4s, 0, 4s + 2\} \in \widetilde{H}_n, \\ f(0) = R, f(4s) = B, f(4s + 2) \neq B. \end{array} \right\} \Rightarrow f(4s + 2) = R,$$

$$\left. \begin{array}{l} \varepsilon_1 + 8s = \{8s, 4s, 8s + 2\} \in \widetilde{H}_n, \\ f(4s) = B, f(8s) = Y, f(8s + 2) \neq Y. \end{array} \right\} \Rightarrow f(8s + 2) = B$$

and

$$\left. \begin{array}{l} \varepsilon_1 + 2 = \{2, 8s + 2, 4\}, \varepsilon_2 = \{0, 8s, 4\} \in \widetilde{H}_n, \\ f(0) = R, f(2) = Y, f(8s) = Y, f(8s + 2) = B. \end{array} \right\} \Rightarrow f(4) = Y.$$

Again, using the automorphism $x \mapsto x - 2$ we reduce the proof to the first case. ■

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