



## New characterization of some linear groups

A. Khalili Asboei <sup>\*†</sup>, R. Mohammadyari <sup>‡</sup>, M. Rahimi-Esbo <sup>§</sup>

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### Abstract

There are a few finite groups that are determined up to isomorphism solely by their order, such as  $\mathbb{Z}_2$  or  $\mathbb{Z}_{15}$ . Still other finite groups are determined by their order together with other data, such as the number of elements of each order, the structure of the prime graph, the number of order components, the number of Sylow  $p$ -subgroups for each prime  $p$ , etc. In this paper, we investigate the possibility of characterizing the projective special linear groups  $L_n(2)$  by simple conditions when  $2^n - 1$  is a prime number. Our result states that:  $G \cong L_n(2)$  if and only if  $|G| = |L_n(2)|$  and  $G$  has one conjugacy class length  $\frac{|L_n(2)|}{2^n - 1}$ , where  $2^n - 1 = p$  is a prime number. Furthermore, we will show that Thompson's conjecture holds for the simple groups  $L_n(2)$ , where  $2^n - 1$  prime is a prime number. By Thompson's conjecture if  $L$  is a finite non-Abelian simple group,  $G$  is a finite group with a trivial center, and the set of the conjugacy classes size of  $L$  is equal to  $G$ , then  $L \cong G$ .

*Keywords* : Projective special linear groups; conjugacy class size; Thompson's conjecture.

## 1 Introduction

Throughout this paper, groups under consideration are finite, and by a simple group, we always mean a non-Abelian simple. In this paper, we investigate the possibility of characterizing  $L_n(2)$  by simple conditions when  $2^n - 1$  is a prime number.

For related results, Chen et al. in [5] shows that the projective special linear groups  $L_2(p)$  recognizable by their order and one conjugacy class length, where  $p$  is a prime number. As a consequence of their result, they showed that Thompson's conjecture is valid for  $L_2(p)$ .

Put  $N(G) = \{n : G \text{ has a conjugacy class of size } n\}$ . By Thompson's conjecture if  $L$  is a finite non-Abelian simple group,  $G$  is a finite group with a trivial center, and  $N(G) = N(L)$ , then  $L \cong G$ .

Similar characterizations have been found in [11] for the groups: sporadic simple groups, and simple  $K_3$ -groups (a finite simple group is called a simple  $K_n$ -group if its order is divisible by exactly  $n$  distinct primes).

The *prime graph* of a finite group  $G$  that denoted by  $\Gamma(G)$  is the graph whose vertices are the prime divisors of  $G$  and where prime  $p$  is defined to be adjacent to prime  $q$  ( $\neq p$ ) if and only if  $G$  contains an element of order  $pq$ .

We denote by  $\pi(G)$  the set of prime divisors of  $|G|$ . Let  $t(G)$  be the number of connected components of  $\Gamma(G)$  and let  $\pi_1, \pi_2, \dots, \pi_{t(G)}$  be the connected components of  $\Gamma(G)$ . If  $2 \in \pi(G)$ , then we always suppose  $2 \in \pi_1$ .

We can express  $|G|$  as a product of integers  $m_1,$

\*Corresponding author. khaliliasbo@yahoo.com

<sup>†</sup>Young Researchers Club and Elite, Buinzahra Branch, Islamic Azad University, Buinzahra, Iran.

<sup>‡</sup>Young Researchers Club and Elite, Buinzahra Branch, Islamic Azad University, Buinzahra, Iran.

<sup>§</sup>Young Researchers Club and Elite, Buinzahra Branch, Islamic Azad University, Buinzahra, Iran.

$m_2, \dots, m_{t(G)}$ , where  $\pi(m_i) = \pi_i$  for each  $i$ . The numbers  $m_i$  are called the order components of  $G$ . In particular, if  $m_i$  is odd, then we call it an odd component of  $G$ . Write  $OC(G)$  for the set  $\{m_1, m_2, \dots, m_{t(G)}\}$  of order components of  $G$  and  $T(G)$  for the set of connected components of  $G$ . According to the classification theorem of finite simple groups and [10, 12, 9], we can list the order components of finite simple groups with disconnected prime graphs as in Tables 1-4 in [4].

If  $n$  is an integer, then denote the  $r$ -part of  $n$  by  $n_r = r^a$  or by  $r^a \parallel n$ , namely,  $r^a \mid n$  but  $r^{a+1} \nmid n$ . The other notation and terminology in this paper are standard, and the reader is referred to [6] if necessary.

### 2 Preliminary Results

For the proof of the main theorem we need to the following Lemmas:

**Lemma 2.1** [7, Lemma 8.1] *Let  $q > 1$  be an integer,  $m$  be a nature number, and  $p$  be an odd prime. If  $p$  divides  $q - 1$ , then  $(q^m - 1)_p = m_p \cdot (q - 1)_p$ .*

**Lemma 2.2** [13] *Let  $a, b$  and  $n$  be positive integers such that  $(a, b) = 1$ . Then there exists a prime  $p$  with the following properties:*

- $p$  divides  $a^n - b^n$ ,*
- $p$  does not divide  $a^k - b^k$  for all  $k < n$ , with the following exceptions:  $a = 2, b = 1, n = 6$  and  $a + b = 2^k, n = 2$ .*

**Remark 2.1** *If  $b = 1$ , the prime  $p$  is called the Zsigmondy prime. If  $p$  is a Zsigmondy of  $a^n - 1$ , then Fermat's little theorem shows that  $n \mid p - 1$ . Put  $Z_n(a) = \{p : p \text{ is a Zsigmondy prime of } a^n - 1\}$ . If  $r \in Z_n(a)$  and  $r \mid a^m - 1$ , then  $n \mid m$ .*

### 3 Main results

By [1, Corollary 2.11],  $L_n(2)$  has one conjugacy class length  $\frac{|L_n(2)|}{2^n - 1}$ .

**Theorem 3.1** *Let  $G$  be a group. Then  $G \cong L_n(2)$  if and only if  $|G| = |L_n(2)|$  and  $G$  has one conjugacy class length  $\frac{|L_n(2)|}{2^n - 1}$ , where  $2^n - 1 = p$  is a prime number.*

**Proof.** The necessity of the theorem can be checked easily. We only need to prove the sufficiency. Since  $2^n - 1$  is a prime, by [8],  $n$  is a prime. If  $n = 2$  or  $3$ , then since  $L_2(2) \cong S_3$  and  $L_3(2) \cong L_2(7)$ , by [5]  $G \cong L_n(2)$ . Thus we only consider that  $n \geq 5$ .

By hypothesis, there exists an element  $x$  of order  $p$  in  $G$  such that  $C_G(x) = \langle x \rangle$  and  $C_G(x)$  is a Sylow  $p$ -subgroup of  $G$ . By the Sylow theorem, we have that  $C_G(y) = \langle y \rangle$  for any element  $y$  in  $G$  of order  $p$ . So,  $\{p\}$  is a prime graph component of  $G$  and  $t(G) \geq 2$ . In addition,  $p$  is the maximal prime divisor of  $|G|$  and an odd order component of  $G$ . We are going to prove the theorem 3.1 in the following steps.

**Step 1.**  $G$  has a normal series  $1 \trianglelefteq H \trianglelefteq K \trianglelefteq G$  such that  $H$  and  $G/K$  are  $\pi_1$ -groups,  $K/H$  is a non-Abelian simple group and  $H$  is a nilpotent group.

Let  $g \in G$  be an element of order  $p$ , then  $C_G(g) = \langle g \rangle$ . Set  $H = O_{p'}(G)$  (the largest normal  $p'$ -subgroup of  $G$ ). Then  $H$  is a nilpotent group since  $g$  acts on  $H$  fixed point freely. Let  $K$  be a normal subgroup of  $G$  such that  $K/H$  is a minimal normal subgroup of  $G/H$ . Then  $K/H$  is a direct product of copies of some simple group. Since  $p \mid |K/H|$  and  $p^2 \nmid |K/H|$ ,  $K/H$  is a simple group. Since  $\langle g \rangle$  is a Sylow  $p$ -subgroup of  $K$ ,  $G = N_G(\langle g \rangle)K$  by the Frattini argument and so  $|G/K|$  divides  $p - 1$ .

If  $|K/H| = p$ , then by Lemma 2.2, there is a prime  $r \in Z_{n-1}(2) \cap \pi(G)$  and so  $|L_n(2)|_r = |2^{n-1} - 1|_r \leq |G|_r$ . Since  $\pi(G) = \pi(K) \cup \pi(H) = \pi_1(G) \cup \pi_2(G)$ , then  $r \in \pi(H)$ . Since  $H$  is nilpotent, a Sylow  $r$ -subgroup is normal in  $G$ . It follows that the Sylow  $p$ -subgroup of  $G$  acts fixed point freely on the set of elements of order  $r$  and so  $p \mid |L_n(2)|_r - 1$ . Thus  $p \leq |L_n(2)|_r \leq ((2^{\frac{n-1}{2}} - 1)^2)_r < 2^{n-1} - 1 < p$ ; a contradiction.

If  $K/H$  has an element of order  $rq$  where  $r$  and  $q$  are primes, then  $G$  has also such element. Hence by definition of order components, an odd order component of  $G$  must be an odd order component of  $K/H$ . Note that  $t(K/H) \geq 2$ .

**Step 2.**  $K/H$  is isomorphic to  $L_n(2)$ .

According to the classification theorem of finite simple groups and the results in Tables 1-4 in [4],  $K/H$  is an alternating group, sporadic group or simple group of Lie type.

First we prove that  $K/H$  can not be an alternating group  $A_m$ .

Let  $K/H \cong A_m$  with  $m \geq 5$ , then since  $2^n - 1 = p$  is a prime and  $p \in \pi(K/H)$ ,  $m \geq 2^n - 1$ . Thus there is a prime  $u \in \pi(A_m) \cap \pi(G)$  such that  $\frac{p+1}{2} < u < p$ . Since  $|G| = |L_n(2)|$ , there exists  $t \in \{2i, i : 1 < i < n - 1\} \cup \{n\}$  such that  $u \in Z_t(2)$ . Obviously  $u > \frac{2^n-1+1}{2} = 2^{n-1}$  and so  $u = 2^{n-1} + 1$ . Since  $n, u$  are primes, then  $n - 1 = 2^k + 1$  and so  $n = 2$ ; a contradiction.

Let  $K/H$  be sporadic simple groups, we can rule out this case by considering their odd order component since the odd components of  $K/H$  is  $p = 2^n - 1$ . Therefore,  $K/H$  is isomorphic to a simple group of Lie type. We consider the following cases.

**Case 1:** Let  $t(K/H) = 2$ . Then we have that  $OC_2(K/H) = p = 2^n - 1$ .

**1.1.** Let  $K/H = C_m(q)$ , where  $m = 2^u > 2$ , then  $\frac{q^m+1}{(2, q-1)} = 2^n - 1$ . If  $q$  is odd, then  $q^m - 1 = 2^{n+1} - 4$ . On the other hand,  $q^m - 1 = 2^2(2^{n-1} - 1)$ . Since  $2 \mid (q - 1)$  and  $m = 2^u$ , then by Lemma 2.1,  $(q^m - 1)_2 = (q - 1)_2 \cdot m_2 = 2^2$ . But  $m \geq 3$ ,  $(q^m - 1)_2 \cdot m_2 \geq 2^3$ ; a contradiction. If  $q$  is even, then  $q^m - 1 = 2^{n-1} - 1$  and hence,  $m = 1, n = 1$ ; a contradiction.

Similarly, we can rule out the cases  $K/H = B_m(q)$  or  $C_m(q)$  with  $m = 2^u \geq 4$ .

**1.2.** Let  $K/H = C_r(3)$  or  $B_r(3)$ , then  $\frac{3^r-1}{2} = 2^n - 1$ . Thus  $3^r = 2^{n+1} - 1$ , which contradicts Lemma 2.2.

Similarly, we can rule out these cases  $K/H = D_r(3)$  or  $D_{r+1}(3)$ .

**1.3.** Let  $K/H = C_r(2)$ , then  $2^r - 1 = 2^n - 1$  and so  $n = r$ . Therefore,  $2^n + 1 \mid |G| = |L_n(2)|$ ; a contradiction. Similarly we can rule out the cases  $K/H = D_r(2)$  or  $D_{r+1}(2)$ .

**1.4.** Let  $K/H = D_r(5)$  where  $r \geq 5$ , then  $\frac{5^r-1}{4} = 2^n - 1$ . Thus  $5^r = 2^{n+2} - 3$  and so  $r = 1 = n$  or  $r = 3, n = 5$ ; a contradiction.

**1.5.** Let  $K/H = {}^2D_m(3)$ , where  $9 \leq m = 2^r + 1$  and  $m$  is not a prime, then  $\frac{3^{m-1}+1}{2} = 2^n - 1$  and hence,  $3(3^{m-2} - 1) = 2^n$ ; a contradiction. Also we can rule out  $K/H = {}^2D_{m+1}(2)$ .

**1.6.** Let  $K/H = {}^2D_m(2)$ , where  $m = 2^r + 1 \geq 5$ , then  $2^{m-1} + 1 = 2^n - 1$  and hence,  $2^{m-2} = 2^{n-1} - 1$ ; a contradiction.

**1.7.** Let  $K/H = {}^2D_r(3)$ , where  $r \neq 2^m + 1 \geq 5$ , then  $\frac{3^r+1}{4} = 2^n - 1$  and hence,  $3^r = 2^{n+2} - 5$ . Thus  $n = 3$  and  $r = 3$ ; a contradiction.

**1.8.** Let  $K/H = G_2(q)$ , where  $2 < q \equiv \varepsilon \pmod 3$  and  $\varepsilon = \pm 1$ , then  $q^2 - \varepsilon q + 1 = 2^n - 1$  and hence,  $(q - 2)(q + 1) = 2^n$  or  $(q + 2)(q - 1) = 2^n$  and hence,  $q = 2$  or  $3$  and  $n = 2$ ; a contradiction.

**1.9.** Let  $K/H = {}^2F_4(2)$ . Since  $|{}^2F_4(2)| = 2^{11} \cdot 3^3 \cdot 5^2 \cdot 13$ ,  $2^n - 1 = 13$ ; a contradiction. Also we can rule out  $K/H = {}^2A_3(2)$ .

**1.10.** Let  $K/H = L_r(q)$ , where  $(r, q) \neq (3, 2), (3, 4)$ . Since  $\frac{q^r-1}{(q-1)(r, q-1)} = 2^n - 1$ , then  $r = n$  and  $q = 2$ , as desired.

**1.11.** Let  $K/H = U_r(q)$ , then  $\frac{q^r+1}{(q+1)(r, q+1)} = 2^n - 1$ .

(a) Let  $q$  is odd. If  $(r, q + 1) = 1$ , then  $q^{r-1} - q^{r-2} + \dots - q + 1 = 2^n - 1$  and hence,  $q^{r-1} - q^{r-2} + \dots - q = 2(2^{n-1} - 1)$ . It follows that  $q = 2$ ; a contradiction. If  $(r, q + 1) = r$ , then  $r = 2$  or  $3 \leq r$  is a prime.

If  $r = 2$ , then  $(q + 1) \mid (q^2 + 1)$ ; a contradiction. Thus  $r \geq 3$  and so  $r \mid (q + 1) \mid (q^r + 1)$ . It follows that  $r \mid q^{2r} - 1$ . Then by Fermat's little theorem,  $r \mid \varphi(2r) = r - 1$ , and so  $r = 1$ ; a contradiction.

(b) Let  $q$  is even. If  $(r, q + 1) = 1$ , then  $q^{r-1} - q^{r-2} + \dots - q + 1 = 2^n - 1$  and hence,  $q^{r-1} - q^{r-2} + \dots - q = 2(2^{n-1} - 1)$ . It follows that  $q = 2$  and  $r = 2$ ; a contradiction. If  $(r, q + 1) = r$ , then  $3 \leq r$  is a prime and so  $r \mid (q + 1) \mid (q^r + 1)$ . It follows that  $r \mid q^{2r} - 1$ . Then by Fermat's little theorem,  $r \mid \varphi(2r) = r - 1$ , and so  $r = 1$ ; a contradiction.

**1.12.** Let  $K/H = L_{r+1}(q)$ , with  $(q - 1) \mid (r - 1)$ . Since  $\frac{q^r-1}{(r, q-1)} = p$ ,  $p \in Z_r(q)$  and hence  $r \mid (p - 1) = 2^n - 2 = 2(2^{n-1} - 1)$ . It follows that  $r = 2$  or  $r \in Z_{n-1}(2)$ .

(a) Let  $r = 2$ . Then  $q = 4$  or  $2$ . If  $q = 4$ , then  $p = 15$ ; a contradiction. Hence  $q = 2, p = 3$  and  $n = 2$ . It follows that  $K/H$  is isomorphic to  $L_3(2)$ , as desired.

(b) Let  $r \in Z_{n-1}(2)$ . Then  $(q-1) \mid (2^n - 1)$  and so  $q$  is a Mersenne prime. Order consideration also rules out this case.

Similarly we can rule out the case  $K/H = U_{r+1}(q)$ .

**1.13.** Let  $K/H = E_6(q)$ , where  $q = u^a$ , then  $\frac{q^6+q^3+1}{(3,q-1)} = p = 2^n - 1$ . Thus  $p \in Z_9(q)$  and hence,  $9 \mid (2^n - 2) = 2(2^{n-1} - 1)$ . It follows that  $9 \mid (2^{n-1} - 1)$  and so  $2 \mid n - 1$  or  $4 \mid n - 1$ . Thus  $n = 2t + 1$  or  $n = 4t + 1$ .

(a) Let  $n = 2t + 1$ . Then  $p = 2^{2t} - 1 = (2^t - 1)(2^t + 1)$  and so  $t = 1$ ,  $p = 3$  and  $n = 2$ . Hence  $\frac{q^6+q^3+1}{(3,q-1)} = 3$ , but the equation has no solution in  $\mathbb{N}$ .

(b) Let  $n = 4t + 1$ . Then  $p = (2^{2t} - 1)(2^{2t} + 1)$ , the equation has no solution in  $\mathbb{N}$ .

Similarly, we can rule out the case  $K/H = {}^2 E_6(q)$ .

**Case 2:** Let  $t(K/H) = 3$ . Then  $p = 2^n - 1 \in \{OC_2(K/H), OC_3(K/H)\}$ .

**2.1.** Let  $K/H = L_2(q)$ , where  $4 \mid (q + 1)$ . Then  $\frac{q-1}{2} = 2^n - 1$  or  $q = 2^n - 1$ . If  $\frac{q-1}{2} = 2^n - 1$ , then  $4 \mid (q + 1) = 2^n$  and so  $n \geq 2$ . If  $n \geq 3$ , then order consideration rules out this case. If  $n = 2$ , then  $q = 7$  and so  $|K/H| \mid |L_2(7)| \mid |L_2(2)|$ ; contradiction. If  $q = 2^n - 1 = p$  and so  $n \geq 2$ , similarly, we can rule out this case.

**2.2.** Let  $K/H = L_2(q)$ , where  $4 \mid (q - 1)$ . Then  $q = p$  or  $\frac{q+1}{2} = p$ . If  $q = p$ , then  $4 \mid (2^n - 2)$ ; a contradiction. If  $\frac{q+1}{2} = p$ , then  $4 \mid (2^{n+1} - 3)$ ; a contradiction.

**2.3.** Let  $K/H = L_2(q)$ , where  $q > 2$  and  $q$  is even. Then  $p \in \{q - 1, q + 1\}$ . If  $p = q - 1$ , then  $q = p + 1 = 2^n$  and so  $(2^n + 1) \mid |G|$ ; a contradiction. If  $p = q + 1$ , then  $q = p - 1 = 2(2^{n-1} - 1)$  and so  $n = 2$ ; a contradiction.

**2.4.** Let  $K/H = U_6(2)$ . Then  $|K/H| = 2^{15} \cdot 3^6 \cdot 7 \cdot 11$  and so  $2^n - 1 = 11$ ; a contradiction.

**2.5.** Let  $K/H = L_3(2)$ . Then  $|K/H| = 2^3 \cdot 3 \cdot 7$  and  $2^n - 1 = 7$ . Thus  $n = 3$ , which is the desired result.

**2.6.** Let  $K/H = {}^2 D_r(3)$ , where  $r = 2^t + 1 \geq 5$ . Then  $\frac{3^r+1}{4} = 2^n - 1$  or  $\frac{3^{r-1}+1}{2} = 2^n - 1$ . If

$\frac{3^r+1}{4} = 2^n - 1$ , then  $3(3^{r-1} - 1) = 2^3(2^{n-1} - 1)$ . Since  $2 \mid 3 - 1$ , then by Lemma 2.1,  $r - 1 = 4$  and so  $t = 2$ . It follows that  $30 = 2^{n-1} - 1$ ; a contradiction. If  $\frac{3^{r-1}+1}{2} = 2^n - 1$ , then  $3^{r-1} = 2(2^{n-1} - 1)$ ; a contradiction.

**2.7.** Let  $K/H = G_2(q)$ , where  $q \equiv 0 \pmod{3}$ . Then  $q^2 - q + 1 = 2^n - 1$  or  $q^2 + q + 1 = 2^n - 1$ . If  $q^2 - q + 1 = 2^n - 1$ , then  $q(q - 1) = 2(2^{n-1} - 1)$  and so  $q = 3$  and  $n = 3$ . Order consideration rules out this case.

If  $q^2 + q + 1 = 2^n - 1$ , then  $q(q + 1) = 2(2^{n-1} - 1)$ . But the equation has no solution in  $\mathbb{N}$ .

Similarly, we can rule out  $K/H = {}^2 G_2(q)$ .

**2.8.** Let  $K/H = F_4(q)$ , where  $q$  is even. Then  $q^4 + 1 = 2^n - 1$  or  $q^4 - q^2 + 1 = 2^n - 1$ . If  $q^4 + 1 = 2^n - 1$ , then  $q^4 = 2(2^{n-1} - 1)$ ; a contradiction. If  $q^4 - q^2 + 1 = 2^n - 1$ , then  $q^2(q^2 - 1) = 2(2^{n-1} - 1)$ , but the equation has no solution in  $\mathbb{N}$ .

**2.9.** Let  $K/H = {}^2 F_4(q)$ , where  $q = 2^{2t} + 1 > 2$ . Then  $q^2 + \sqrt{2q^3} + q + \sqrt{2q} + 1 = 2^n - 1$  or  $q^2 - \sqrt{2q^3} + q - \sqrt{2q} + 1 = 2^n - 1$ . It is easy to get that the equations  $q^2 + \sqrt{2q^3} + q + \sqrt{2q} + 1 = 2(2^{n-1} - 1)$  and  $q^2 - \sqrt{2q^3} + q - \sqrt{2q} + 1 = 2(2^{n-1} - 1)$  have no solution in  $\mathbb{N}$ .

**2.10.** Let  $K/H = E_7(2)$ , then  $2^n - 1 \in \{73, 127\}$  and so  $n = 7$ . Order consideration rules out this case.

**2.11.** Let  $K/H = E_7(3)$ , then  $2^n - 1 \in \{757, 1093\}$ , which is impossible.

**Case 3:** Let  $t(K/H) = \{4, 5\}$ . Then  $p = 2^n - 1 \in \{OC_2(K/H), OC_3(K/H), OC_4(K/H), OC_5(K/H)\}$ .

**3.1.** Let  $K/H = L_3(4)$  or  ${}^2 E_6(2)$ . Then  $2^n - 1 = 7$  or  $2^n - 1 = 19$ . If  $2^n - 1 = 7$ , then  $n = 3$ , and then order consideration rules out. If  $2^n - 1 = 19$ , then it is impossible.

**3.2.** Let  $K/H = {}^2 B_2(q)$ , where  $q = 2^{2t} + 1$  and  $t \geq 1$ . Then  $2^n - 1 \in \{q - 1, q \pm \sqrt{2q} + 1\}$ . If  $2^n - 1 = q - 1$ , then  $n = 2^t + 1$ , order consideration rules out. If  $2^n - 1 = q \pm \sqrt{2q} + 1$ , then  $2(2^{n-1} - 1) = 2^{t+1}(2^t - 1)$ . The equation has no solution in  $\mathbb{N}$ .

Hence  $K/H = L_n(2)$  with  $2^n - 1$  prime. Now since  $|G| = |L_n(2)|$ ,  $H = 1$  and  $K = G \cong L_n(2)$ . The Theorem 3.1 is proved.

**Corollary 3.1** *Thompson's conjecture holds for the simple groups  $L_n(2)$ , where  $2^n - 1$  prime is a prime number.*

**Proof.** Let  $G$  be a group with a trivial central and  $N(G) = N(L_n(2))$ . Then it is proved in [2, Lemma 1.4] that  $|G| = |L_n(2)|$ . Hence; the corollary follows from the Theorem 3.1.

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Alireza Khalili Asboei, he has born in the Mazandaran, Babol in 1972. Got B.Sc degree in pure mathematics from Teacher Training University, M. Sc degree in pure mathematics, finite group theory field from Tarbiat Modares University, and PHD degree in pure mathematics, finite group theory field from Science and Research Branch, Islamic Azad University. Main research interest include finite groups, finite simple groups, permutations groups, and characterization of finite groups.



Reza Mohammadyari, he has born in the Tehran in 1982. Got B.Sc degree in pure mathematics from University of Tehran, M. Sc degree in pure mathematics, graph theory field from University of Tehran, and PHD degree in pure mathematics, graph theory field from Science and Research Branch, Islamic Azad University. Main research interest include graph theory, finite groups, and energy conversion. At present, he is an assistant professor of mathematics at Azad University, located at Buinzahra.



Mazaher Rahimi-Esbo, he has born in the Mazandaran, Babol in 1987. He studied at the field of mathematics physics at high school. He could graduate at the field of mechanical engineering at B.C. in Babol University of Technology. He studied in the field of energy conversion at M. Sc period in Babol University of Technology. At present, he is Ph.D student in Babol University of Technology at field of energy conversion.