

# Graphs encoding the generating properties of a finite group

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## Abstract

Assume that  $G$  is a finite group. For every  $a, b \in \mathbb{N}$ , we define a graph  $\Gamma_{a,b}(G)$  whose vertices correspond to the elements of  $G^a \cup G^b$  and in which two tuples  $(x_1, \dots, x_a)$  and  $(y_1, \dots, y_b)$  are adjacent if and only if  $\langle x_1, \dots, x_a, y_1, \dots, y_b \rangle = G$ . We study several properties of these graphs (isolated vertices, loops, connectivity, diameter of the connected components) and we investigate the relations between their properties and the group structure, with the aim of understanding which information about  $G$  is encoded by these graphs.

## KEYWORDS

finite group, generating graph, generation, probabilistic zeta function, swap conjecture

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## 1 | INTRODUCTION

The generating graph  $\Gamma(G)$  of a finite group  $G$  is the graph defined on the elements of  $G$  in such a way that two distinct vertices are connected by an edge if and only if they generate  $G$ . It was defined by Liebeck and Shalev in [22], and has been further investigated by many authors: see for example [4–8, 10, 20, 25, 27, 28, 31] for some of the range of questions that have been considered. Many deep structural results about finite groups can be expressed in terms of the generating graph, but of course  $\Gamma(G)$  encodes significant information only when  $G$  is a 2-generator group. The aim of this paper is to introduce and investigate a wider family of graphs which encode the generating property of  $G$  when  $G$  is an arbitrary finite group.

We introduce the following definition. Assume that  $G$  is a finite group and let  $a$  and  $b$  be nonnegative integers. We define an undirected graph  $\Gamma_{a,b}(G)$  whose vertices correspond to the elements of  $G^a \cup G^b$  and in which two tuples  $(x_1, \dots, x_a)$  and  $(y_1, \dots, y_b)$  are adjacent if and only if  $\langle x_1, \dots, x_a, y_1, \dots, y_b \rangle = G$ . Notice that  $\Gamma_{1,1}(G)$  is the generating graph of  $G$ , so these graphs can be viewed as a natural generalization of the generating graph.

There may be many isolated vertices in the generating graph  $\Gamma(G)$  of a finite group  $G$  (for example if  $N$  is a normal subgroup of  $G$  and  $G/N$  is not cyclic, then all the elements of  $N$  correspond to isolated vertices). However, [10] considers the subgraph  $\Gamma^*(G)$  of  $\Gamma(G)$  that is induced by all of the vertices that are not isolated and it is proved that if  $G$  is a 2-generator soluble group, then  $\Gamma^*(G)$  is connected. This result is equivalent to saying the “swap conjecture” is satisfied by the 2-generator finite soluble groups. Recall that the swap conjecture concerns the connectivity of the graph  $\Sigma_d(G)$  in which the vertices are the ordered generating  $d$ -tuples and two vertices  $(x_1, \dots, x_d)$  and  $(y_1, \dots, y_d)$  are adjacent if and only if they differ only by one entry. Tennant and Turner [34] conjectured that the swap graph is connected for every group. Roman’kov [33] proved that the free metabelian group of rank 3 does not satisfy this conjecture but no counterexample is known in the class of finite groups. There is a strong relation between the properties of the swap graph  $\Sigma_{a+b}(G)$  and those of the graph  $\Gamma_{a,b}^*(G)$ , obtained from  $\Gamma_{a,b}(G)$  by deleting the isolated vertices. In particular we prove that if  $\Sigma_{a+b}(G)$  is connected, then  $\Gamma_{a,b}^*(G)$  is also connected (see Lemma 2.6). Recently [10, 15] it has been proved that  $\Sigma_d(G)$  is connected

if either  $d > d(G)$  or  $d = d(G)$  and  $G$  is soluble (where  $d(G)$  is the minimum number of generators of  $G$ ). This can be used to prove the connectivity of  $\Gamma_{a,b}^*(G)$  in many cases: *the graphs  $\Gamma_{a,b}^*(G)$  are connected, except possibly when  $a + b = d(G)$  and  $G$  is not soluble* (see Corollary 2.7).

Once is known that the graphs  $\Gamma_{a,b}^*(G)$  are connected in most cases, the next step is to investigate their diameters. When  $G$  is soluble and 2-generated, it has been recently proved [24] that the graph  $\Gamma^*(G)$  has diameter at most 3: this bound is best possible, but it can be improved to 2 if  $G$  satisfies the following additional property:  $|\text{End}_G(V)| > 2$  for every non-trivial irreducible  $G$ -module  $V$  which is  $G$ -isomorphic to a complemented chief factor of  $G$  (which is true for example if the derived subgroup of  $G$  is nilpotent or has odd order). In this paper we prove a more general result (see Theorem 3.10):

*Assume that  $G$  is a finite soluble group and that  $(x_1, \dots, x_b)$  and  $(y_1, \dots, y_b)$  are non-isolated vertices of  $\Gamma_{a,b}(G)$ : if either  $a \neq 1$  or  $|\text{End}_G(V)| > 2$  for every non-trivial irreducible  $G$ -module  $V$  which is  $G$ -isomorphic to a complemented chief factor of  $G$ , then there exists  $(z_1, \dots, z_a) \in G^a$  such that  $G = \langle z_1, \dots, z_a, x_1, \dots, x_b \rangle = \langle z_1, \dots, z_a, y_1, \dots, y_b \rangle$ .*

We will give an example showing that when  $a = 1$  the previous statement does not remain true if we drop the assumption on the order of the endomorphism group of the complemented chief factors. But in any case the previous result allows us to conclude that  $\text{diam}(\Gamma_{a,b}^*(G)) \leq 4$  whenever  $G$  is soluble and  $a + b \geq d(G)$  (see Corollary 3.11). These results lead also to a better understanding of the swap graph. For example we deduce that if  $G$  is soluble and  $|\text{End}_G(V)| > 2$  for every non-trivial irreducible  $G$ -module  $V$  which is  $G$ -isomorphic to a complemented chief factor of  $G$ , then the diameter of the swap graph  $\Sigma_d(G)$  is at most  $2d - 1$  (see Theorem 3.13).

The bound  $\text{diam}(\Gamma_{a,b}^*(G)) \leq 4$  that we prove for finite soluble groups cannot be generalized to an arbitrary finite group. Assume that  $S$  is a finite non-abelian simple group and, for  $d \geq 2$ , let  $\tau_d(S)$  be the largest positive integer  $r$  such that  $S^r$  can be generated by  $d$  elements. In Section 4 we will prove that if  $a$  and  $b$  are positive integers, then  $\Gamma_{a,b}^*(S^{\tau_{a+b}(S)})$  is connected, however

$$\lim_{p \rightarrow \infty} \text{diam}(\Gamma_{a,b}^*(\text{SL}(2, 2^p)^{\tau_{a+b}(\text{SL}(2, 2^p))})) = \infty.$$

In Section 5 we investigate how one can deduce information on  $G$  from the knowledge of the graphs  $\Gamma_{a,b}^*(G)$  for all the possible choices of  $a$  and  $b$ . More precisely we will denote by  $\Lambda^*(G)$  the collection of all the connected components of the graphs  $\Gamma_{a,b}^*(G)$ , for all the possible choices of  $a, b$  in  $\mathbb{N}$ . However for each of the graphs in this family, we do not assume to know from which choice of  $a, b$  it arises. Roughly speaking, we can think that we packaged all the graphs  $\Gamma_{a,b}^*(G)$  in a (quite spacious) box but that we did not pay enough attention during this operation and we lost the information to which group  $G$  these graphs correspond and the labels  $a, b$ : do not panic, a big amount of the lost information can be reconstructed! We prove that from the knowledge of  $\Lambda^*(G)$  we may recover  $d(G)$ ,  $|G|$  and the labels  $a, b$ , at least when  $a + b > d(G)$  (see Propositions 5.9, 5.14 and 5.13). Moreover, considerations on the number of edges of the graphs in  $\Lambda^*(G)$  allow us to determine, for every  $t \in \mathbb{N}$ , the number  $\phi_G(t)$  of the ordered generating  $t$ -tuples of  $G$ . Philip Hall [21] observed that the probability  $\phi_G(t)/|G|^t$  of generating a given finite group  $G$  by a random  $t$ -tuple of elements is given by

$$P_G(t) = \sum_{n \in \mathbb{N}} \frac{a_n(G)}{n^t}$$

where  $a_n(G) = \sum_{|G:H|=n} \mu_G(H)$  and  $\mu$  is the Möbius function on the subgroup lattice of  $G$ . In other words, for a given finite group  $G$ , there exists a uniquely determined Dirichlet polynomial  $P_G(s)$  (where  $s$  is a complex variable) with the property that for  $t \in \mathbb{N}$  the number  $P_G(t)$  coincides with the probability of generating  $G$  by  $t$  randomly chosen elements. The reciprocal of  $P_G(s)$  is the “probabilistic zeta function” of  $G$ , studied by N. Boston [2], A. Mann [30] and the second named author [13]. We prove that  $P_G(s)$  can be determined from  $\Lambda^*(G)$  (see Theorem 5.15) and consequently we may also recover from  $\Lambda^*(G)$  all the information that can be determined from  $P_G(s)$ , taking advantages from a series of available results in the literature, about the relation between the arithmetic properties of the Dirichlet series  $P_G(s)$  and the structure of  $G$ . In particular we may deduce whether  $G$  is soluble or supersoluble and, for every prime power  $n$ , determine the number of maximal subgroups of  $G$  of index  $n$ . But we also prove that from  $\Lambda^*(G)$  we may deduce whether  $G$  is nilpotent and the order of the Frattini subgroup (information that cannot be recovered from  $P_G(s)$ ). A possible development of this investigation could be to minimize the number of graphs in  $\Lambda^*(G)$  that have to be considered in order to obtain information about  $G$ . From this point of view, we notice that all the above mentioned properties of  $G$  could be deduced taking into account only the graphs of the form  $\Gamma_{1,b}^*(G)$  for  $b \in \mathbb{N}$ .

The graphs  $\Gamma_{1,b}(G)$  play also a central role in the last section of the paper. In [8] an equivalence relation  $\equiv_m$  has been introduced, where two elements are equivalent if each can be substituted for the other in any generating set for  $G$ . This

relation can be refined to a new sequence  $\equiv_m^{(r)}$  of equivalence relations by saying that  $x \equiv_m^{(r)} y$  if each can be substituted for the other in any  $r$ -element generating set. The relations  $\equiv_m^{(r)}$  become finer as  $r$  increases, and in [8] the authors study the value  $\psi(G)$  of  $r$  at which they stabilise to  $\equiv_m$ . Indeed results about  $\equiv_m, \equiv_m^{(r)}$  and  $\psi(G)$  can be reformulated and reinterpreted in terms of properties of the graphs  $\Gamma_{1,b}(G)$ . A significant role in this investigation is played by the groups  $G$  with the property that  $(g)$  is not isolated in the graph  $\Gamma_{1,d(G)-1}(G)$  for every  $g \neq 1$  (generalising a terminology used for 2-generator groups, we say that  $G$  has non-zero spread if it satisfies such property). In [3], Breuer, Guralnick and Kantor make the following remarkable conjecture: “A 2-generated finite group has non-zero spread if and only if every proper quotient is cyclic.” This conjecture has been recently proved by Burness, Guralnick and Harper [7]. In the final part of the paper we generalize this result, proving that a finite group  $G$  has non-zero spread if and only if  $d(G/N) < d(G)$  for every non-trivial normal subgroup  $N$  of  $G$ .

## 2 | THE GRAPHS $\Gamma_{a,b}(G)$ AND $\Gamma_{a,b}^*(G)$

In this section we give the definition of the graphs  $\Gamma_{a,b}(G)$  and  $\Gamma_{a,b}^*(G)$  associated to a finite group  $G$  and a pair  $(a, b)$  of nonnegative integers. Firstly we explore some properties of these graphs that follow easily from their definitions and then we investigate their connection with the so called “swap graph”. In particular we use this connection in order to deduce results about the connectivity of  $\Gamma_{a,b}(G)$  and  $\Gamma_{a,b}^*(G)$ .

Let  $G$  be a finite group. We will denote by  $d(G)$  the smallest cardinality of a generating set of  $G$ . Moreover, given  $d \in \mathbb{N}$ , we will denote by  $\Phi_G(d)$  the set of the ordered generating  $d$ -tuples of  $G$  and by  $\phi_G(d)$  the cardinality of this set.

**Definition 2.1.** Assume that  $G$  is a finite group and let  $a$  and  $b$  be nonnegative integers with  $a \leq b$ . We define an undirected graph  $\Gamma_{a,b}(G)$  whose vertices correspond to the elements of  $G^a \cup G^b$  and in which two tuples  $(x_1, \dots, x_a)$  and  $(y_1, \dots, y_b)$  are adjacent if and only  $\langle x_1, \dots, x_a, y_1, \dots, y_b \rangle = G$ .

Clearly if  $a + b < d(G)$ , then  $\Gamma_{a,b}(G)$  is an empty graph, so in general we will implicitly assume  $a + b \geq d(G)$ .

**Definition 2.2.**  $\Gamma_{a,b}^*(G)$  is the graph obtained from  $\Gamma_{a,b}(G)$  by deleting the isolated vertices.

In the particular case when  $a = 0$ , the graph  $\Gamma_{0,b}^*(G)$  is a star with one internal node, corresponding to the 0-tuple, and  $\phi_G(b)$  leaves, corresponding to the ordered generating  $b$ -tuples of  $G$ . Notice that if  $a \geq d(G)$ , then  $\Gamma_{a,a}(G)$  contains loops: if  $G = \langle g_1, \dots, g_a \rangle$  then we have a loop around the vertex  $(g_1, \dots, g_a)$ .

Let  $d = a + b$ . If  $a \neq b$  then  $\Gamma_{a,b}(G)$  and  $\Gamma_{a,b}^*(G)$  are bipartite graphs with two parts, one corresponding to the elements of  $G^a$  and the other to the elements of  $G^b$ . We will use the notations  $V_a$  and  $V_b$  for the vertices of  $\Gamma_{a,b}^*(G)$  corresponding, respectively, to elements of  $G^a$  and  $G^b$ . In particular  $\Gamma_{a,b}(G)$  has  $|G|^a + |G|^b$  vertices and there exists a bijective correspondence between  $\Phi_G(d)$  and the set of the edges of  $\Gamma_{a,b}(G)$ : indeed if  $\langle g_1, \dots, g_d \rangle = G$ , then  $(g_1, \dots, g_a)$  and  $(g_{a+1}, \dots, g_d)$  are adjacent vertices of the graph. Hence the number of edges of  $\Gamma_{a,b}(G)$  (which coincides with the number of edges of  $\Gamma_{a,b}^*(G)$ ) is  $\phi_G(d)$ . The situation is different if  $a = b$ . In that case  $\Gamma_{a,a}(G)$  has  $|G|^a$  vertices,  $\phi_G(a)$  loops and other  $(\phi_G(d) - \phi_G(a))/2$  edges connecting two different vertices (in other words if  $e$  is the the number of edges, excluding the loops, and  $l$  is the number of loops, then  $2e + l = \phi_G(d)$ ); indeed the two elements  $(g_1, \dots, g_a, g_{a+1}, \dots, g_d)$  and  $(g_{a+1}, \dots, g_d, g_1, \dots, g_a)$  give rise to the same edge in  $\Gamma_{a,a}(G)$ .

**Lemma 2.3.** Let  $G$  be any non-trivial finite group and let  $a$  be any positive integer. Then any edge, which is not a loop, of the graph  $\Gamma_{a,a}^*(G)$  lies in a 3-cycle, except when  $a = 1$  and  $G \cong C_2$ .

*Proof.* Take any edge in  $\Gamma_{a,a}^*(G)$ , which is not a loop, and let us call  $x = (x_1, \dots, x_a)$  and  $y = (y_1, \dots, y_a)$  its vertices. If  $x$  and  $y$  are different from the tuple  $(1, \dots, 1)$ , then both vertices are adjacent to a third vertex  $z = (x_1 y_1, \dots, x_a y_a)$  and we are done. Next assume that one vertex, let us say  $y$ , has all trivial entries. This implies that  $x$  is a generating  $a$ -tuple for  $G$ , so the vertex  $x$  is adjacent to all other vertices of  $\Gamma_{a,a}^*(G)$ . If  $(a, G) \neq (1, C_2)$ , then there exists a generating  $a$ -tuple for  $G$  different from  $x$ , and this is adjacent to both  $x$  and  $y$ . This concludes the proof.  $\square$

From the previous lemma it follows that no connected component of  $\Gamma_{a,a}^*(G)$  is bipartite since a graph is bipartite if and only if it contains no odd cycles. Observe that if  $G = 1$ , then, for every  $a \in \mathbb{N}$ , the graph  $\Gamma_{a,a}^*(G)$  consists of a unique vertex with a loop, so it is not bipartite either. In the case where  $G$  is isomorphic to  $C_2$  and  $a = 1$ , the graph  $\Gamma_{1,1}^*(G)$  is again not bipartite since we have a loop on the vertex corresponding to the unique generator of  $G$ .

**Lemma 2.4.** *If  $|G| \geq 3$ , then  $\Gamma_{a,b}^*(G)$  contains a vertex  $x$  of degree 1 if and only if  $a = 0$ ,  $b \geq d(G)$  and  $x$  is one of the  $\phi_G(b)$  leaves of the star  $\Gamma_{0,b}^*(G) \cong K_{1,\phi_G(b)}$ .*

*Proof.* Assume that  $x$  is a vertex of degree 1 in  $\Gamma_{a,b}^*(G)$  and that  $a > 0$ . We may assume  $x = (x_1, \dots, x_r)$  with  $r \in \{a, b\}$ . Let  $s = a + b - r$ . Then there exists  $(y_1, \dots, y_s)$  such that  $G = \langle x_1, \dots, x_r, y_1, \dots, y_s \rangle$ . If  $x_i \neq 1$  for some  $i \in \{1, \dots, r\}$ , then  $x$  is also adjacent to the tuple  $(x_i y_1, y_2, \dots, y_s)$ , a contradiction. So  $x = (1, \dots, 1)$  and consequently  $y = (y_1, \dots, y_s)$  is a tuple of generators for  $G$ . For every  $\pi \in \text{Sym}(s)$ , the element  $y_\pi = (y_{1\pi}, \dots, y_{s\pi})$  is adjacent to  $x$ . Since  $x$  has degree 1, we must have  $y_1 = \dots = y_s$ ,  $G = \langle y_1 \rangle$  and  $y_1$  is the unique element generating  $G$ : this implies  $|G| \leq 2$ .  $\square$

The Möbius function  $\mu_G$  is the function defined on the lattice of subgroups of  $G$  by  $\sum_{K \geq H} \mu_G(K) = \delta_{H,G}$ , where  $\delta_{G,G} = 1$  and  $\delta_{H,G} = 0$  if  $H \neq G$ . The following is a consequence of [23, Sect. 3].

**Lemma 2.5.** *Let  $a$  and  $b$  be nonnegative integers. Let  $x = (x_1, \dots, x_r) \in G^r$  with  $r \in \{a, b\}$  and set  $K = \langle x_1, \dots, x_r \rangle$ ,  $s = a + b - r$  and let  $\delta_{a,b}(x)$  be the degree of  $x$  in  $\Gamma_{a,b}(G)$ . We have*

$$\delta_{a,b}(x) = \sum_{K \leq H} \mu_G(H) |H|^s.$$

*In particular  $|K|^s$  divides the degree  $\delta_{a,b}(x)$  of  $x$  in  $\Gamma_{a,b}(G)$ .*

Recall that for a  $d$ -generator finite group  $G$ , the swap graph  $\Sigma_d(G)$  is the graph in which the vertices are the ordered generating  $d$ -tuples and in which two vertices  $(x_1, \dots, x_d)$  and  $(y_1, \dots, y_d)$  are adjacent if and only if they differ only by one entry.

**Lemma 2.6.** *If  $\Sigma_{a+b}(G)$  is connected, then  $\Gamma_{a,b}^*(G)$  is connected.*

*Proof.* Let  $d = a + b$ . We write any generating  $d$ -tuple  $\omega$  in the form  $\omega = (\alpha, \beta)$ , with  $\alpha \in G^a$  and  $\beta \in G^b$ . Now let  $\sigma, \sigma^*$  be two non-isolated vertices of  $\Gamma_{a,b}^*(G)$ : there exist two generating  $d$ -tuples  $\omega = (\alpha, \beta)$  and  $\omega^* = (\alpha^*, \beta^*)$  with  $\sigma \in \{\alpha, \beta\}$  and  $\sigma^* \in \{\alpha^*, \beta^*\}$ . Since  $\Sigma_d(G)$  is connected, there exists a path in  $\Sigma_d(G)$  joining  $\omega$  to  $\omega^*$ . In order to complete our proof, it suffices to prove that if

$$\omega_1 = (\alpha_1, \beta_1), \dots, \omega_u = (\alpha_u, \beta_u)$$

is a path in  $\Sigma_d(G)$ , then the vertices  $\alpha_1, \beta_1, \alpha_2, \beta_2, \dots, \alpha_u, \beta_u$  belong to the same connected component of  $\Gamma_{a,b}^*(G)$ . We prove this claim by induction on  $u$ . The sentence is clearly true when  $u = 1$ . Assume  $u \geq 2$ . By induction  $\alpha_2, \beta_2, \dots, \alpha_u, \beta_u$  belong to the same connected component of  $\Gamma_{a,b}^*(G)$ ; so it is enough to show that  $\alpha_1, \beta_1, \alpha_2, \beta_2$  belong to the same connected component. Since  $(\alpha_1, \beta_1)$  and  $(\alpha_2, \beta_2)$  differ for only one entry, either  $\alpha_1 = \alpha_2$  or  $\beta_1 = \beta_2$ . The graph  $\Gamma_{a,b}^*(G)$  contains the path  $\beta_1, \alpha_1 = \alpha_2, \beta_2$  in the first case and the path  $\alpha_1, \beta_1 = \beta_2, \alpha_2$  in the second case.  $\square$

The swap conjecture states that  $\Sigma_d(G)$  is connected for every finite group  $G$  and every  $d \geq d(G)$ . In [11] it was proved that this conjecture is true if  $d > d(G)$ , while in [16] it is proved that it is true also when  $d = d(G)$  and  $G$  is soluble. So we have:

**Corollary 2.7.** *If  $G$  is a finite group and either  $a + b > d(G)$  or  $a + b = d(G)$  and  $G$  is soluble, then  $\Gamma_{a,b}^*(G)$  is connected.*

It remains an open problem to decide whether  $\Gamma_{a,b}^*(G)$  is connected when  $a + b = d(G)$  and  $G$  is unsoluble. We conjecture that the answer is positive. However we think that proving results in this direction would be quite difficult and would require deep information about the generation properties of the finite almost simple groups.

We conclude this section, with the following result, that will be used later.

**Lemma 2.8.** *Let  $N$  be a normal subgroup of a finite group  $G$  and let  $a$  and  $b$  be nonnegative integers and assume that  $a + b \geq d(G)$ . If  $\Gamma_{a,b}^*(G)$  is connected, then  $\Gamma_{a,b}^*(G/N)$  is connected too.*

This lemma is an easy consequence of the following result due to Gaschütz [17].

**Theorem 2.9.** *Let  $G$  be any group that can be generated by  $d$  elements and let  $N$  be any finite normal subgroup of  $G$ . Let  $\eta : G \rightarrow \bar{G} = G/N$  be the natural homomorphism given by  $\eta : g \rightarrow \bar{g} = Ng$  for all  $g \in G$ . Then for any generating  $d$ -tuple  $(y_1, y_2, \dots, y_d)$  of elements of  $G/N$  there exist elements  $x_1, x_2, \dots, x_d \in G$  such that  $\langle x_1, x_2, \dots, x_d \rangle = G$  and  $\bar{x}_i = y_i$  for  $1 \leq i \leq d$ .*

### 3 | BOUNDING THE DIAMETER OF $\Gamma_{a,b}^*(G)$ WHEN $G$ IS SOLUBLE

In [24] it is proved that if  $G$  is a 2-generator finite soluble group, then the graph  $\Gamma_{1,1}^*(G)$  obtained from the generating graph by removing the isolated vertices has a very small diameter: indeed  $\text{diam}(\Gamma_{1,1}^*(G)) \leq 3$ . Moreover,  $\text{diam}(\Gamma_{1,1}^*(G)) \leq 2$  if  $G$  has the property that  $|\text{End}_G(V)| > 2$  for every non-trivial irreducible  $G$ -module  $V$  which is  $G$ -isomorphic to a complemented chief factor of  $G$ . The aim of this section is to bound  $\text{diam}(\Gamma_{a,b}^*(G))$  for arbitrary values of  $a$  and  $b$  when  $G$  is soluble.

Before dealing with the general case of a soluble group  $G$ , we need to collect in the next four lemmas a series of results in linear algebra. Denote by  $M_{r \times s}(F)$  the set of the  $r \times s$  matrices with coefficients over the field  $F$ .

**Lemma 3.1.** [10, Lemma 3] *Let  $V$  be a finite dimensional vector space over the field  $F$ . If  $W_1$  and  $W_2$  are subspaces of  $V$  with  $\dim W_1 = \dim W_2$ , then  $V$  contains a subspace  $U$  such that  $V = W_1 \oplus U = W_2 \oplus U$ .*

**Lemma 3.2.** *Assume that  $a$  and  $b$  are nonnegative integers. Let  $V$  be a vector space of dimension  $\delta$  over a finite field  $F$  and let  $x = (v_1, \dots, v_a)$  and  $y = (w_1, \dots, w_a)$  be two elements of  $V^a$  with  $\dim_F \langle v_1, \dots, v_a \rangle \geq \delta - b$  and  $\dim_F \langle w_1, \dots, w_a \rangle \geq \delta - b$ . Then there exists  $z = (z_1, \dots, z_b) \in V^b$  such that  $\langle v_1, \dots, v_a, z_1, \dots, z_b \rangle = \langle w_1, \dots, w_a, z_1, \dots, z_b \rangle = V$ .*

*Proof.* Let  $U_1 = \langle v_1, \dots, v_a \rangle$ ,  $U_2 = \langle w_1, \dots, w_a \rangle$  and  $s = \min\{\dim_F U_1, \dim_F U_2\}$ . Clearly we may assume  $s < \delta$ . We prove our claim by induction on  $s$ . If  $s = 0$ , then  $b \geq \delta$  and it suffices to choose  $z_1, \dots, z_b$  so that  $\langle z_1, \dots, z_b \rangle = V$ . Assume  $s \neq 0$ . Notice that  $b + s \geq \delta$ . Let  $\tilde{v}_1, \dots, \tilde{v}_s$  be linearly independent elements of  $U_1$  and  $\tilde{w}_1, \dots, \tilde{w}_s$  linearly independent elements of  $U_2$ . Moreover, let  $\tilde{U}_1 = \langle \tilde{v}_1, \dots, \tilde{v}_s \rangle$  and  $\tilde{U}_2 = \langle \tilde{w}_1, \dots, \tilde{w}_s \rangle$ . Since  $|\tilde{U}_1 \cup \tilde{U}_2| \leq 2|F|^s - 1 < |F|^\delta$ , there exists  $\tilde{z} \in V \setminus (\tilde{U}_1 \cup \tilde{U}_2)$ . Consider  $\tilde{x} = (\tilde{v}_1, \dots, \tilde{v}_s, \tilde{z})$  and  $\tilde{y} = (\tilde{w}_1, \dots, \tilde{w}_s, \tilde{z})$ . Since  $(s + 1) + (b - 1) \geq \delta$  and  $\dim_F \langle \tilde{v}_1, \dots, \tilde{v}_s, \tilde{z} \rangle = \dim_F \langle \tilde{w}_1, \dots, \tilde{w}_s, \tilde{z} \rangle = s + 1$ , by induction there exist  $\tilde{z}_1, \dots, \tilde{z}_{b-1}$  such that  $\langle \tilde{v}_1, \dots, \tilde{v}_s, \tilde{z}, \tilde{z}_1, \dots, \tilde{z}_{b-1} \rangle = \langle \tilde{w}_1, \dots, \tilde{w}_s, \tilde{z}, \tilde{z}_1, \dots, \tilde{z}_{b-1} \rangle = V$ . Clearly  $z = (\tilde{z}, \tilde{z}_1, \dots, \tilde{z}_{b-1})$  satisfies the conditions  $\langle v_1, \dots, v_a, z, \tilde{z}_1, \dots, \tilde{z}_{b-1} \rangle = \langle w_1, \dots, w_a, z, \tilde{z}_1, \dots, \tilde{z}_{b-1} \rangle = V$ .  $\square$

**Lemma 3.3.** *Let  $F$  be a finite field and assume  $\alpha \leq \beta$ . Given  $R \in M_{\alpha \times \beta}(F)$  and  $S \in M_{\alpha \times \gamma}(F)$  consider the matrix  $(R S) \in M_{\alpha \times (\beta + \gamma)}$ . Assume that  $\text{rank}(R S) = \alpha$  and let  $\pi_{R,S}$  be the probability that a matrix  $Z \in M_{\gamma \times \beta}(F)$  satisfies the condition  $\text{rank}(R + SZ) = \alpha$ . Then*

$$\pi_{R,S} > 1 - \frac{q^\alpha}{q^\beta(q-1)}.$$

*Proof.* There exist  $m \leq \min\{\alpha, \gamma\}$ ,  $X \in \text{GL}(\alpha, F)$  and  $Y \in \text{GL}(\gamma, F)$  such that

$$XSY = \begin{pmatrix} I_m & 0_{m \times (\gamma - m)} \\ 0_{(\alpha - m) \times m} & 0_{(\alpha - m) \times (\gamma - m)} \end{pmatrix},$$

where  $I_m$  is the identity element in  $M_{m \times m}(F)$ . Since

$$\alpha = \text{rank}(R S) = \text{rank}\left(X (R S) \begin{pmatrix} I_\beta & 0_{\beta \times \gamma} \\ 0_{\gamma \times \beta} & Y \end{pmatrix}\right) = \text{rank}(X R X S Y)$$

and

$$\text{rank}(R + S Z) = \text{rank}(X(R + S Z)) = \text{rank}(X R + X S Z) = \text{rank}(X R + X S Y (Y^{-1} Z)),$$

it is not restrictive (replacing  $R$  by  $X R$ ,  $S$  by  $X S Y$  and  $Z$  by  $Y^{-1} Z$ ) to assume

$$S = \begin{pmatrix} I_m & 0_{m \times (\gamma - m)} \\ 0_{(\alpha - m) \times m} & 0_{(\alpha - m) \times (\gamma - m)} \end{pmatrix}.$$

Denote by  $v_1, \dots, v_\alpha$  the rows of  $R$  and by  $z_1, \dots, z_\gamma$  the rows of  $Z$ . The fact that the rows of  $(R S)$  are linearly independent implies that  $v_{m+1}, \dots, v_\alpha$  are linearly independent vectors of  $F^\beta$ . The condition  $\text{rank}(R + S Z) = \alpha$  is equivalent to asking that

$$v_1 + z_1, \dots, v_m + z_m, v_{m+1}, \dots, v_\alpha$$

are linearly independent. The probability that  $z_1, \dots, z_m$  satisfy this condition is

$$\left(1 - \frac{q^{\alpha - m}}{q^\beta}\right) \left(1 - \frac{q^{\alpha - m + 1}}{q^\beta}\right) \dots \left(1 - \frac{q^{\alpha - m + (m - 1)}}{q^\beta}\right).$$

Hence

$$\begin{aligned} \pi_{R,S} &= \left(1 - \frac{q^{\alpha - m}}{q^\beta}\right) \left(1 - \frac{q^{\alpha - m + 1}}{q^\beta}\right) \dots \left(1 - \frac{q^{\alpha - m + (m - 1)}}{q^\beta}\right) \\ &\geq 1 - \frac{q^{\alpha - m}(1 + q + \dots + q^{m - 1})}{q^\beta} \\ &= 1 - \frac{q^{\alpha - m}(q^m - 1)}{q^\beta(q - 1)} > 1 - \frac{q^\alpha}{q^\beta(q - 1)}. \end{aligned}$$

□

**Lemma 3.4.** Let  $F$  be a finite field. Given positive integers  $u, v, n, t$  satisfying  $n \leq \min\{u, v\}$  and  $t + n = u + v$ , suppose that  $A_1, A_2 \in M_{n \times u}(F)$ ,  $B \in M_{n \times v}(F)$ ,  $D_1, D_2 \in M_{t \times u}(F)$  with the property that

$$\text{rank}\begin{pmatrix} B & A_1 \\ C & D_1 \end{pmatrix} = \text{rank}\begin{pmatrix} B & A_2 \\ C & D_2 \end{pmatrix} = n,$$

$$\text{rank}\begin{pmatrix} A_1 \\ D_1 \end{pmatrix} = \text{rank}\begin{pmatrix} A_2 \\ D_2 \end{pmatrix} = u.$$

Then there exists  $C \in M_{t \times v}(F)$  such that

$$\det\begin{pmatrix} B & A_1 \\ C & D_1 \end{pmatrix} \neq 0 \quad \text{and} \quad \det\begin{pmatrix} B & A_2 \\ C & D_2 \end{pmatrix} \neq 0,$$

except when  $|F| = 2$ ,  $n = v$  and  $\det B \neq 0$ .

*Proof.* Let  $r = \text{rank}(B)$ . There exist  $X \in \text{GL}(n, F)$  and  $Y \in \text{GL}(v, F)$  such that

$$XBY = \begin{pmatrix} I_r & 0_{r \times (v-r)} \\ 0_{(n-r) \times r} & 0_{(n-r) \times (v-r)} \end{pmatrix},$$

where  $I_r$  is the identity element in  $M_{r \times r}(F)$ . Let  $A_{11}, A_{21} \in M_{r \times u}(F)$  and  $A_{12}, A_{22} \in M_{(n-r) \times u}(F)$  such that

$$XA_1 = \begin{pmatrix} A_{11} \\ A_{12} \end{pmatrix}, \quad XA_2 = \begin{pmatrix} A_{21} \\ A_{22} \end{pmatrix}.$$

For  $i \in \{1, 2\}$ , since

$$n = \text{rank} \begin{pmatrix} B & A_i \end{pmatrix} = \text{rank} \left( X \begin{pmatrix} B & A_i \end{pmatrix} \begin{pmatrix} Y & 0_{v \times u} \\ 0_{u \times v} & I_u \end{pmatrix} \right) = \text{rank} \begin{pmatrix} I_r & 0_{r \times (v-r)} & A_{i1} \\ 0_{(n-r) \times r} & 0_{(n-r) \times (v-r)} & A_{i2} \end{pmatrix},$$

it must be  $\text{rank}(A_{i2}) = n - r$ . In particular there exists  $Z_i \in \text{GL}(u, F)$  such that

$$XA_i Z_i = \begin{pmatrix} A_{i1} \\ A_{i2} \end{pmatrix} Z_i = \begin{pmatrix} A_{i1}^* & A_{i2}^* \\ 0_{(n-r) \times u - (n-r)} & I_{n-r} \end{pmatrix},$$

with  $A_{i1}^* \in M_{r \times u - (n-r)}(F)$  and  $A_{i2}^* \in M_{r \times (n-r)}(F)$ . Notice that

$$\det \begin{pmatrix} XBY & XA_i Z_i \\ CY & D_i Z_i \end{pmatrix} = \det \left( \begin{pmatrix} X & 0_{n \times t} \\ 0_{t \times n} & I_t \end{pmatrix} \begin{pmatrix} B & A_i \\ C & D_i \end{pmatrix} \begin{pmatrix} Y & 0_{v \times u} \\ 0_{u \times v} & Z_i \end{pmatrix} \right) = \det(X) \det(Y) \det(Z_i) \det \begin{pmatrix} B & A_i \\ C & D_i \end{pmatrix}.$$

This means that it is not restrictive to assume

$$B = \begin{pmatrix} I_r & 0_{r \times (v-r)} \\ 0_{(n-r) \times r} & 0_{(n-r) \times (v-r)} \end{pmatrix}, \quad A_i = \begin{pmatrix} A_{i1}^* & A_{i2}^* \\ 0_{(n-r) \times u - (n-r)} & I_{n-r} \end{pmatrix},$$

with  $A_{i1}^* \in M_{r \times u - (n-r)}(F)$ ,  $A_{i2}^* \in M_{r \times (n-r)}(F)$ . Let  $C_1 \in M_{t \times r}(F)$ ,  $C_2 \in M_{t \times v - r}(F)$ ,  $D_{i1} \in M_{t \times u - (n-r)}(F)$ ,  $D_{i2} \in M_{t \times (n-r)}(F)$  such that

$$(C_1 \ C_2) = C \quad \text{and} \quad (D_{i1} \ D_{i2}) = D_i.$$

Notice that

$$\begin{aligned} \det \begin{pmatrix} B & A_i \\ C & D_i \end{pmatrix} &= \det \begin{pmatrix} I_r & 0_{r \times (v-r)} & A_{i1}^* & A_{i2}^* \\ 0_{(n-r) \times r} & 0_{(n-r) \times (v-r)} & 0_{(n-r) \times u - (n-r)} & I_{n-r} \\ C_1 & C_2 & D_{i1} & D_{i2} \end{pmatrix} \\ &= (-1)^{n-r} \det \begin{pmatrix} I_r & 0_{r \times (v-r)} & A_{i1}^* \\ C_1 & C_2 & D_{i1} \end{pmatrix} \\ &= (-1)^{n-r} \det \left( \begin{pmatrix} I_r & 0_{r \times (v-r)} & A_{i1}^* \\ C_1 & C_2 & D_{i1} \end{pmatrix} \begin{pmatrix} I_r & 0_{r \times (v-r)} & -A_{i1}^* \\ 0_{(v-r) \times r} & I_{v-r} & 0_{(v-r) \times u - (n-r)} \\ 0_{u - (n-r) \times r} & 0_{u - (n-r) \times (v-r)} & I_{u - (n-r)} \end{pmatrix} \right) \\ &= (-1)^{n-r} \det \begin{pmatrix} I_r & 0_{r \times (v-r)} & 0_{r \times u - (n-r)} \\ C_1 & C_2 & D_{i1} - C_1 A_{i1}^* \end{pmatrix} \\ &= (-1)^{n-r} \det(C_2 \ D_{i1} - C_1 A_{i1}^*). \end{aligned}$$

Assume that we can find  $C_1$  such that

$$\text{rank}(D_{11} - C_1 A_{11}^*) = \text{rank}(D_{21} - C_1 A_{21}^*) = u - (n - r)$$

and let  $W_1, W_2$  be the subspaces of  $F^t$  spanned, respectively, by the columns of the two matrices  $D_{11} - C_1 A_{11}^*$  and  $D_{21} - C_1 A_{21}^*$ . By Lemma 3.1, there exists a subspace  $U$  of  $F^t$  such that  $F^t = W_1 \oplus U = W_2 \oplus U$ . If  $C_2$  is a matrix whose columns are a basis for  $U$ , then

$$\det\left(C_2 \quad D_{11} - C_1 A_{11}^*\right) \neq 0 \text{ and } \det\left(C_2 \quad D_{21} - C_1 A_{21}^*\right) \neq 0$$

and  $C = (C_1 \ C_2)$  is a matrix with the desired property. Set

$$R_1 = D_{11}^T, \quad R_2 = D_{21}^T, \quad S_1 = A_{11}^{*T}, \quad S_2 = A_{21}^{*T}, \quad Z = -C_1^T.$$

The previous observation implies that a matrix  $C$  with the requested properties exists if, and only if, there exists  $Z \in M_{r \times t}(F)$  such that

$$\text{rank}(R_1 + S_1 Z) = \text{rank}(R_2 + S_2 Z) = u - (n - r). \tag{3.1}$$

Notice that  $R_1, R_2 \in M_{u-(n-r) \times t}(F)$ ,  $S_1, S_2 \in M_{u-(n-r) \times r}(F)$  are such that

$$\text{rank}\begin{pmatrix} R_1 & S_1 \end{pmatrix} = \text{rank}\begin{pmatrix} R_2 & S_2 \end{pmatrix} = u - (n - r).$$

If either  $|F| = q > 2$  or  $u - (n - r) < t$ , then, by applying Lemma 3.3 with  $\alpha = u - (n - r), \beta = t, \gamma = r$ , we have

$$\pi_{R_1, S_1} > \frac{1}{2} \quad \text{and} \quad \pi_{R_2, S_2} > \frac{1}{2}$$

and this is sufficient to ensure that a matrix  $Z$  with the requested property exists. Therefore we may assume  $u - (n - r) = t$  and  $q = 2$ . This implies that  $v = r$ , and so that  $v = n = r$ , i.e.  $\det B \neq 0$ . This concludes the proof.  $\square$

The main ingredient in the proof of our results about the diameter of  $\Gamma_{a,b}^*(G)$  is the theory of crowns, introduced by Gaschütz in [19]. We recall some properties of the crowns of a finite soluble group. Let  $G$  be a finite soluble group, and let  $\mathcal{V}_G$  be a set of representatives for the irreducible  $G$ -groups that are  $G$ -isomorphic to a complemented chief factor of  $G$ . For  $V \in \mathcal{V}_G$  let  $R_G(V)$  be the smallest normal subgroup contained in  $C_G(V)$  such that  $C_G(V)/R_G(V)$  is  $G$ -isomorphic to a direct product of copies of  $V$  and it has a complement in  $G/R_G(V)$ . The factor group  $C_G(V)/R_G(V)$  is called the  $V$ -crown of  $G$ . The nonnegative integer  $\delta_G(V)$  defined by  $C_G(V)/R_G(V) \cong_G V^{\delta_G(V)}$  is called the  $V$ -rank of  $G$  and it coincides with the number of complemented factors in any chief series of  $G$  that are  $G$ -isomorphic to  $V$ . If  $\delta_G(V) \neq 0$ , then the  $V$ -crown is the socle of  $G/R_G(V)$ .

**Proposition 3.5.** [25, Proposition 2.4] *Let  $G$  and  $\mathcal{V}_G$  be as above. Let  $x_1, \dots, x_u$  be elements of  $G$  such that  $\langle x_1, \dots, x_u, R_G(V) \rangle = G$  for any  $V \in \mathcal{V}_G$ . Then  $\langle x_1, \dots, x_u \rangle = G$ .*

**Lemma 3.6.** [1, Lemma 1.3.6] *Let  $G$  be a finite soluble group with trivial Frattini subgroup. There exists a crown  $C/R$  and a non-trivial normal subgroup  $U$  of  $G$  such that  $C = R \times U$ .*

**Lemma 3.7.** [15, Proposition 11] *Assume that  $G$  is a finite soluble group with trivial Frattini subgroup and let  $C, R, U$  be as in the statement of Lemma 3.6. If  $HU = HR = G$ , then  $H = G$ .*

Now let  $V$  be a finite dimensional vector space over a finite field of prime order. Let  $K$  be a  $d$ -generated linear soluble group acting irreducibly and faithfully on  $V$  and fix a generating  $d$ -tuple  $(k_1, \dots, k_d)$  of  $K$ . For a positive integer  $u$  we consider the semidirect product  $G_u = V^u \rtimes K$ , where  $K$  acts in the same way on each of the  $u$  direct factors. We will use the aforementioned properties of the crowns, in particular Proposition 3.5 and Lemmas 3.6 and 3.7, to essentially reduce

the study of the graph  $\Gamma_{a,b}^*(G)$  to the particular case when  $G \cong G_u$ . Put  $F = \text{End}_K(V)$ . Let  $n$  be the dimension of  $V$  over  $F$ . We may identify  $K = \langle k_1, \dots, k_d \rangle$  with a subgroup of the general linear group  $\text{GL}(n, F)$ . In this identification  $k_i$  becomes an  $n \times n$  matrix  $X_i$  with coefficients in  $F$ ; denote by  $A_i$  the matrix  $I_n - X_i$ . Let  $w_i = (v_{i,1}, \dots, v_{i,u}) \in V^u$ . Then every  $v_{i,j}$  can be viewed as a  $1 \times n$  matrix. Denote the  $u \times n$  matrix with rows  $v_{i,1}, \dots, v_{i,u}$  by  $D_i$ . The following result is proved in [9, Sect. 2].

**Proposition 3.8.** *The group  $G_u = V^u \rtimes K$  can be generated by  $d$  elements if and only if  $u \leq n(d-1)$ . Moreover,*

1.  $\text{rank}(A_1 \ \dots \ A_d) = n$ .
2.  $\langle k_1 w_1, \dots, k_d w_d \rangle = V^u \rtimes K$  if and only if  $\text{rank} \begin{pmatrix} A_1 & \dots & A_d \\ D_1 & \dots & D_d \end{pmatrix} = n + u$ .

The next result may seem rather technical, but it provides crucial information on the graph  $\Gamma_{a,b}(G)$  when  $G \cong V^\delta \rtimes K$ .

**Proposition 3.9.** *Let  $K$  be a non-trivial  $d$ -generator linear soluble group acting irreducibly and faithfully on  $V$  and consider the semidirect product  $G = V^\delta \rtimes K$  with  $\delta \leq n(d-1)$ , where  $n = \dim_{\text{End}_G(V)} V$ . Let  $a$  and  $b$  be nonnegative integers such that  $a + b = d$ ,  $s \in \{a, b\}$  and  $t = d - s$ . Assume that  $(t, |F|) \neq (1, 2)$  and there exist, for  $i \in \{1, 2\}$ ,  $x_{i1}, \dots, x_{is}$  and  $y_1, \dots, y_t$  in  $K$ , and  $w_{i1}, \dots, w_{is}$  in  $V^\delta$  such that*

1.  $(x_{11} w_{11}, \dots, x_{1s} w_{1s})$  and  $(x_{21} w_{21}, \dots, x_{2s} w_{2s})$  are non-isolated vertices belonging to  $V_s$  in the graph  $\Gamma_{a,b}^*(G)$ ,
2.  $\langle x_{11}, \dots, x_{1s}, y_1, \dots, y_t \rangle = \langle y_1, \dots, y_t, x_{21}, \dots, x_{2s} \rangle = K$ .

Then there exist  $w_1, \dots, w_t \in V^\delta$  with

$$\langle x_{11}, \dots, x_{1s}, y_1 w_1, \dots, y_t w_t \rangle = \langle y_1 w_1, \dots, y_t w_t, x_{21}, \dots, x_{2s} \rangle = G.$$

*Proof.* Since  $V^\delta \rtimes K$  is an epimorphic image of  $V^{n(d-1)} \rtimes K$ , it suffices to prove the statement in the particular case where  $G = V^{n(d-1)} \rtimes K$ . We may identify the elements  $x_{i1}, \dots, x_{is}, y_1, \dots, y_t$  with matrices  $X_{i1}, \dots, X_{is}, Y_1, \dots, Y_t \in \text{GL}(n, F)$ , respectively, where  $F = \text{End}_G(V)$  and  $w_{i1}, \dots, w_{is}, w_1, \dots, w_t \in V^{n(d-1)}$  with matrices  $D_{i1}, \dots, D_{is}$  and  $C_1, \dots, C_t$  in  $M_{n(d-1) \times n}(F)$ , respectively. We now apply Proposition 3.8. Let

$$\begin{aligned} A_{ij} &= I_n - X_{ij}, \quad \text{for } i \in \{1, 2\} \text{ and } j \in \{1, \dots, s\}, \\ B_k &= I_n - Y_k, \quad \text{for } k \in \{1, \dots, t\}. \end{aligned}$$

Conditions (1) and (2) imply that

$$\text{rank}(A_{11} \ \dots \ A_{1s} \ B_1 \ \dots \ B_t) = \text{rank}(A_{21} \ \dots \ A_{2s} \ B_1 \ \dots \ B_t) = n$$

and

$$\text{rank} \begin{pmatrix} A_{11} & \dots & A_{1s} \\ D_{11} & \dots & D_{1s} \end{pmatrix} = \text{rank} \begin{pmatrix} A_{21} & \dots & A_{2s} \\ D_{21} & \dots & D_{2s} \end{pmatrix} = ns.$$

Moreover, our statement is equivalent to saying that there exist  $t$  matrices  $C_1, \dots, C_t \in M_{n(d-1) \times n}(F)$  with

$$\det \begin{pmatrix} A_{11} & \dots & A_{1s} & B_1 & \dots & B_t \\ D_{11} & \dots & D_{1s} & C_1 & \dots & C_t \end{pmatrix} \neq 0, \quad \det \begin{pmatrix} B_1 & \dots & B_t & A_{21} & \dots & A_{2s} \\ C_1 & \dots & C_t & D_{21} & \dots & D_{2s} \end{pmatrix} \neq 0.$$

Put, for  $i \in \{1, 2\}$

$$\begin{aligned} A_i &= (A_{i1} \ \dots \ A_{is}) \in M_{n \times ns}(F), \\ D_i &= (D_{i1} \ \dots \ D_{is}) \in M_{n(d-1) \times ns}(F), \\ B &= (B_1 \ \dots \ B_t) \in M_{n \times nt}(F). \end{aligned}$$

The existence of  $C = (C_1 \dots C_t) \in M_{n(d-1) \times nt}(F)$  such that

$$\det \begin{pmatrix} A_1 & B \\ D_1 & C \end{pmatrix} \neq 0, \det \begin{pmatrix} B & A_2 \\ C & D_2 \end{pmatrix} \neq 0$$

is ensured by Lemma 3.4. Notice that the fact that  $K$  is a non-trivial subgroup of  $GL(n, F)$  implies that  $n \geq 2$  if  $|F| = 2$ . Moreover, if  $|F| = 2$  and  $\text{rank } B = \text{rank}(B_1 \dots B_t) = nt$ , we necessarily have  $t = d - s = 1$ .  $\square$

We are now ready to prove the main result of this section.

**Theorem 3.10.** *Let  $G$  be a finite soluble group, let  $a$  and  $b$  be nonnegative integers, let  $s \in \{a, b\}$  and  $t = a + b - s$ . Assume that either  $t \neq 1$  or  $G$  has the following property: if  $A$  is a non-trivial irreducible  $G$ -module  $G$ -isomorphic to a complemented chief factor of  $G$ , then  $|\text{End}_G(A)| > 2$  (this holds in particular when the derived subgroup of  $G$  is either nilpotent or of odd order). Then in the graph  $\Gamma_{a,b}^*(G)$  given any two vertices  $x_1, x_2 \in V_s$ , there exists  $y \in V_t$  which is adjacent to both  $x_1$  and  $x_2$ .*

*Proof.* We may assume  $d := a + b \geq d(G)$ . We argue by induction on the order of  $G$ . Choose two vertices  $x_1 = (x_{11}, \dots, x_{1s})$  and  $x_2 = (x_{21}, \dots, x_{2s})$  in  $V_s$ . Let  $F = \text{Frat}(G)$  be the Frattini subgroup of  $G$ . Clearly  $x_1 F = (x_{11} F, \dots, x_{1s} F)$  and  $x_2 F = (x_{21} F, \dots, x_{2s} F)$  are vertices of the graph  $\Gamma_{a,b}^*(G/F)$ . If  $F \neq 1$ , then, by induction, there exists a  $t$ -tuple  $y F = (y_1 F, \dots, y_t F)$  which is simultaneously adjacent to  $x_1 F$  and  $x_2 F$  in the graph  $\Gamma_{a,b}^*(G/F)$ . This implies that  $G = \langle x_{11}, \dots, x_{1s}, y_1, \dots, y_t \rangle F = \langle x_{21}, \dots, x_{2s}, y_1, \dots, y_t \rangle F = \langle x_{11}, \dots, x_{1s}, y_1, \dots, y_t \rangle = \langle x_{21}, \dots, x_{2s}, y_1, \dots, y_t \rangle$ , hence  $y = (y_1, \dots, y_t)$  is a  $t$ -tuple adjacent to both  $x_1$  and  $x_2$  in  $\Gamma_{a,b}^*(G)$ . Therefore we may assume  $F = 1$ . In this case, by Lemma 3.6, there exist a crown  $C/R$  of  $G$  and a normal subgroup  $U$  of  $G$  such that  $C = R \times U$ . We have  $R = R_G(A)$  where  $A$  is an irreducible  $G$ -module and  $U \cong_G A^\delta$  for  $\delta = \delta_G(A)$ . By induction, in the graph  $\Gamma_{a,b}^*(G/U)$ , there exists a  $t$ -tuple  $y U = (y_1 U, \dots, y_t U)$  which is adjacent to both  $x_1 U = (x_{11} U, \dots, x_{1s} U)$  and  $x_2 U = (x_{21} U, \dots, x_{2s} U)$ . In particular, we have

$$\langle x_{11}, \dots, x_{1s}, y_1, \dots, y_t \rangle U = \langle x_{21}, \dots, x_{2s}, y_1, \dots, y_t \rangle U = G. \tag{3.2}$$

We work in the factor group  $\bar{G} = G/R$ . We have  $\bar{C} = C/R = UR/R \cong U \cong A^\delta$  and either  $A \cong C_p$  is a trivial  $G$ -module and  $\bar{G} \cong (C_p)^\delta$  or  $\bar{G} = \bar{U} \rtimes \bar{H} \cong A^\delta \rtimes K$  where  $K \cong \bar{H}$  acts in the same way on each of the  $\delta$  factors of  $A^\delta$  and this action is faithful and irreducible. Since  $\bar{G}$  is  $d$ -generated, we have  $\delta \leq d$  if  $A$  is a trivial  $G$ -module,  $\delta \leq n(d - 1)$ , where  $n = \dim_{\text{End}_G(A)} A$  otherwise.

By Lemma 3.2 in the first case and by Proposition 3.9 in the second case, there exist  $u_1, \dots, u_t \in U$  with

$$\langle \bar{x}_{11}, \dots, \bar{x}_{1s}, \bar{y}_1 \bar{u}_1, \dots, \bar{y}_t \bar{u}_t \rangle = \langle \bar{y}_1 \bar{u}_1, \dots, \bar{y}_t \bar{u}_t, \bar{x}_{21}, \dots, \bar{x}_{2s} \rangle = \bar{G},$$

i.e.

$$\langle x_{11}, \dots, x_{1s}, y_1 u_1, \dots, y_t u_t \rangle R = \langle y_1 u_1, \dots, y_t u_t, x_{21}, \dots, x_{2s} \rangle R = G. \tag{3.3}$$

In view of Lemma 3.7, from (3.2) and (3.3), we obtain

$$\langle x_{11}, \dots, x_{1s}, y_1 u_1, \dots, y_t u_t \rangle = \langle y_1 u_1, \dots, y_t u_t, x_{21}, \dots, x_{2s} \rangle = G.$$

$\square$

Now from Theorem 3.10 and [24, Thm. 1] we easily deduce the following result.

**Corollary 3.11.** *Let  $G$  be a finite soluble group and let  $a$  and  $b$  be nonnegative integers. Then*

$$\text{diam}(\Gamma_{a,b}^*(G)) \leq 4.$$





$$b_1 := (y, z)((e_1, 0, \dots, 0), (e_1, 0, \dots, 0)),$$

$$b_2 := (y, z)((0, \dots, 0), (e_1, 0, \dots, 0)).$$

It can be easily checked that either  $a_{11}, a_2, \dots, a_{d-1}, b_1$  as  $a_{12}, a_2, \dots, a_{d-1}, b_2$  satisfy the three conditions (1), (2), (3) and therefore

$$\langle a_{11}, a_2, \dots, a_{d-1}, b_1 \rangle = \langle a_{12}, a_2, \dots, a_{d-1}, b_2 \rangle = G.$$

Now we want to prove that there is no  $b \in G$  with

$$\langle a_{11}, a_2, \dots, a_{d-1}, b \rangle = \langle a_{12}, a_2, \dots, a_{d-1}, b \rangle = G.$$

Let  $b = (h_1, h_2)((v_{11}, \dots, v_{1u}), (v_{21}, \dots, v_{2u}))$ , and assume by contradiction that  $\langle a_{11}, a_2, \dots, a_{d-1}, b \rangle = \langle a_{12}, a_2, \dots, a_{d-1}, b \rangle = G$ . We must have in particular that condition (1) holds, i.e.  $\langle (x, x), (h_1, h_2) \rangle = H$ . Since  $(x, x)$  has order 2 and  $H$  cannot be generated by two involutions (otherwise it would be a dihedral group) at least one of the two elements  $h_1, h_2$  must have order 3: it is not restrictive to assume  $h_1 = y$ . Let

$$A = \begin{pmatrix} 1-x & 0_{2 \times 2} & \dots & 0_{2 \times 2} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 \end{pmatrix},$$

$$B = 1 - y = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix},$$

$$C_1 = \begin{pmatrix} 0 & 0 & 0_{2 \times u-2} \\ 0 & 1 & 0_{2 \times u-2} \\ 0_{u-2 \times 2} & I_{u-2} & \end{pmatrix}, \quad C_2 = \begin{pmatrix} 1 & 0 & 0_{2 \times u-2} \\ 0 & 1 & 0_{2 \times u-2} \\ 0_{u-2 \times 2} & I_{u-2} & \end{pmatrix},$$

$$D = \begin{pmatrix} v_{11} \\ \vdots \\ v_{1u} \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \end{pmatrix} \text{ with } D_2 \in M_{u-2 \times 2}(\mathbb{F}_2) \text{ and } D_1 = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}.$$

Condition (2) must be satisfied, hence we must have

$$\det \begin{pmatrix} A & B \\ C_1 & D \end{pmatrix} = \det \begin{pmatrix} A & B \\ C_2 & D \end{pmatrix} = 1.$$

However

$$\det \begin{pmatrix} A & B \\ C_1 & D \end{pmatrix} = \det \begin{pmatrix} 0 & 0 & 0_{2 \times u-2} & 0 & 1 \\ 1 & 0 & 0_{2 \times u-2} & 1 & 1 \\ 0 & 0 & 0_{2 \times u-2} & D_1 & \\ 0 & 1 & 0_{2 \times u-2} & D_1 & \\ 0_{u-2 \times 2} & I_{u-2} & D_2 & \end{pmatrix} = \det \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & \alpha & \beta \\ 0 & 1 & \gamma & \delta \end{pmatrix} = \alpha,$$

$$\det \begin{pmatrix} A & B \\ C_2 & D \end{pmatrix} = \det \begin{pmatrix} 0 & 0 & 0_{2 \times u-2} & 0 & 1 \\ 1 & 0 & 0_{2 \times u-2} & 1 & 1 \\ 1 & 0 & 0_{2 \times u-2} & D_1 & \\ 0 & 1 & 0_{2 \times u-2} & D_1 & \\ 0_{u-2 \times 2} & I_{u-2} & D_2 & \end{pmatrix} = \det \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & \alpha & \beta \\ 0 & 1 & \gamma & \delta \end{pmatrix} = \alpha + 1.$$

However, since  $\alpha \in \mathbb{F}_2$  either  $\alpha = 0$  or  $\alpha + 1 = 0$ , so there is no  $b \in G$  with  $\langle a_{11}, a_2, \dots, a_{d-1}, b \rangle = \langle a_{12}, a_2, \dots, a_{d-1}, b \rangle = G$ .

We conclude this section noticing that Theorem 3.10 can be applied to bound the diameter of the swap graph.

**Theorem 3.13.** *Suppose that a finite soluble group  $G$  has the following property: if  $A$  is a non-trivial irreducible  $G$ -module  $G$ -isomorphic to a complemented chief factor of  $G$ , then  $|\text{End}_G(A)| > 2$  (this holds in particular when the derived subgroup of  $G$  is either nilpotent or of odd order). If  $d \geq d(G)$ , then the diameter of the swap graph  $\Sigma_d(G)$  is at most  $2d - 1$ .*

*Proof.* Assume that  $G = \langle a_1, \dots, a_d \rangle = \langle b_1, \dots, b_d \rangle$ . By Theorem 3.10, there exists  $x_1 \in G$  such that  $G = \langle x_1, a_2, \dots, a_d \rangle = \langle x_1, b_2, \dots, b_d \rangle$ . Applying  $d - 1$  times Theorem 3.10, we find elements  $x_i$ , for  $1 \leq i \leq d - 1$ , satisfying

$$G = \langle x_1, \dots, x_{i-1}, x_i, a_{i+1}, \dots, a_d \rangle = \langle x_1, \dots, x_{i-1}, x_i, b_{i+1}, \dots, b_d \rangle.$$

Hence  $\Sigma_d(G)$  contains the following path of length  $2d - 1$ :

$$\begin{aligned} & (a_1, \dots, a_d), \\ & (x_1, a_2, \dots, a_d), \\ & (x_1, x_2, a_3, \dots, a_d), \\ & \quad \vdots \\ & (x_1, \dots, x_{d-1}, a_d), \\ & (x_1, \dots, x_{d-1}, b_d), \\ & (x_1, \dots, x_{d-1}, b_{d-1}, b_d), \\ & \quad \vdots \\ & (x_1, b_2, \dots, b_d), \\ & (b_1, \dots, b_d). \end{aligned}$$

Since this path has length  $2d - 1$ , we are done. □

## 4 | DIRECT POWERS OF SIMPLE GROUPS

In this section we will try to generalize some results proved in [11] concerning the generating graph of direct powers of non-abelian simple groups. As a by-product, we will see that the bounds on the diameter of the graphs  $\Gamma_{a,b}^*(G)$ , proved in Section 3, does not remain true if we drop the solubility assumption: for every positive integer  $\eta$  and every pair  $a, b$  of positive integers, a finite group  $G$  can be constructed such that  $d(G) = a + b$  and  $\Gamma_{a,b}^*(G)$  is connected with diameter at least  $\eta$ .

Let  $S$  be a non-abelian finite simple group and denote by  $A$  the automorphism group  $\text{Aut}(S)$  of  $S$ . As usual we identify  $S$  with the subgroup of  $A$  consisting of the inner automorphisms. Let  $d \geq 2$  be a positive integer and define  $\tau = \tau_d(S)$  to be the largest positive integer  $r$  such that  $S^r$ , the direct product of  $r$  copies of  $S$ , can be generated by  $d$  elements. Notice that the group  $S^r$  cannot be generated by  $d$  elements whenever  $r$  is larger than the number of  $A$ -orbits on the set of  $d$ -tuples generating  $S$ . Actually,  $\tau$  is equal to the number of  $A$ -orbits on ordered  $d$ -tuples of generators for  $S$  and, for arbitrary elements  $x_1 = (x_{1,1}, \dots, x_{1,\tau}), \dots, x_d = (x_{d,1}, \dots, x_{d,\tau})$  of  $S^\tau$ , we have  $S^\tau = \langle x_1, \dots, x_d \rangle$  if and only if the  $d$ -tuples  $(x_{1,i}, \dots, x_{d,i})$  are distinct representatives for these orbits for  $1 \leq i \leq \tau$ . Let  $K = \text{Aut}(S^\tau)$ . Recall that  $K \cong A \wr \text{Sym}(\tau)$ . Clearly  $K \leq \text{Aut}(\Gamma_{a,b}(S^\tau))$  for every  $a, b$  with  $a + b = d$ . The following easy remark will play a crucial role in our discussion.

**Lemma 4.1.** *Assume  $S^\tau = \langle x_1, \dots, x_d \rangle$ . If  $S^\tau = \langle y_1, \dots, y_d \rangle$ , then there exists  $k \in K$  such that  $(y_1, \dots, y_d) = (x_1^k, \dots, x_d^k)$ .*

*Proof.* Assume  $x_i = (x_{i,1}, \dots, x_{i,\tau}), y_j = (y_{j,1}, \dots, y_{j,\tau})$  for  $1 \leq i, j \leq d$ . Both  $(x_{1,1}, \dots, x_{d,1}), \dots, (x_{1,\tau}, \dots, x_{d,\tau})$  and  $(y_{1,1}, \dots, y_{d,1}), \dots, (y_{1,\tau}, \dots, y_{d,\tau})$  form a set of representatives for the  $A$ -orbits of the set of generating  $d$ -tuples for  $S$ . So there exist  $\pi \in \text{Sym}(\tau)$  and  $(a_1, \dots, a_\tau) \in A^\tau$  such that  $(y_{1,i\pi}, \dots, y_{d,i\pi}) = (x_{1,i}, \dots, x_{d,i})^{a_i}$  for each  $i \in \{1, \dots, \tau\}$ . It follows that  $(y_1, \dots, y_d) = (x_1^k, \dots, x_d^k)$  for  $k = (a_1, \dots, a_\tau)\pi \in K$ . □

**Corollary 4.2.** *Let  $\tau = \tau_{a+b}(S)$ . Then the graph  $\Gamma_{a,b}^*(S^\tau)$  is edge-transitive.*

Now we will introduce other notations, useful to study the graph  $\Gamma_{a,b}(S^\tau)$ . Fix a vertex  $x = (x_1, \dots, x_a)$  in the part  $V_a$  of  $\Gamma_{a,b}^*(S^\tau)$  corresponding to the  $(a)$ -tuples and a vertex  $y = (y_1, \dots, y_b)$  in the part  $V_b$  corresponding to the  $(b)$ -tuples and let  $C = C_K(x)$  and  $D = C_K(y)$ . To describe more precisely  $C$  we need the following information. Let  $s_1, \dots, s_u$  be a set of representatives for the  $A$ -orbits of  $S^a$  that can be completed to a generating  $d$ -tuple of  $S$ . Every vertex  $x \in V_a$  can be viewed as an  $a \times \tau$  matrix  $(x_{i,j})$  with  $x_{i,j} \in S$ . Denote by  $\tau_i$  the number of columns of  $x$  that are  $A$ -conjugate to  $s_i$ . By Corollary 4.2 this number is independent on the choice of  $x$ . In particular  $x$  is  $K$ -conjugate to  $\bar{x}$  with

$$\bar{x} = \left( \underbrace{s_1, \dots, s_1}_{\tau_1 \text{ terms}}, \underbrace{s_2, \dots, s_2}_{\tau_2 \text{ terms}}, \dots, \underbrace{s_u, \dots, s_u}_{\tau_u \text{ terms}} \right).$$

It follows that  $C \cong C_K(\bar{x}) = \prod_{1 \leq i \leq u} C_A(s_i) \wr \text{Sym}(\tau_i)$ . Clearly we have a similar description for  $D = C_K(y)$ , with the only difference that the role of  $s_1, \dots, s_u$  will be played by a set of representatives  $t_1, \dots, t_v$  for the  $A$ -orbits of  $S^b$  that can be completed to a generating  $d$ -tuple of  $S$ .

**Lemma 4.3.** *Assume  $1 \leq a \leq b$  with  $(a, b) \neq (1, 1)$ . For every  $i \neq 1$ , there exists  $\bar{y}_i \in V_a$  such that*

1.  $\bar{x}$  and  $\bar{y}_i$  have a common neighbour in  $\Gamma_{a,b}^*(S^\tau)$ .
2. The first column of  $\bar{y}_i$  is  $A$ -conjugate to  $s_i$ .
3.  $\bar{x}$  and  $\bar{y}_i$  differ only for 2-columns.

*Proof.* Since  $b \geq 2$  and  $d(S) = 2$ , there exists  $i$  such that  $s_i = (1, \dots, 1)$ . Hence we may assume  $s_1 = (1, \dots, 1)$ . Let  $z \in V_b$  be adjacent to  $\bar{x}$  in  $\Gamma_{a,b}^*(S^\tau)$ . We identify  $z$  with a matrix  $(t_1, \dots, t_\tau)$  where  $t_j \in S^b$  for every  $j$ . The columns of the matrix

$$E := \begin{pmatrix} s_1 & \dots & s_1 & \dots & s_u & \dots & s_u \\ t_1 & \dots & t_{\tau_1} & \dots & t_{\tau-\tau_u+1} & \dots & t_\tau \end{pmatrix}$$

are a set of representatives of the  $A$ -orbits on the generating  $d$ -tuples of  $S$ . Since  $s_1 = (1, \dots, 1)$ ,  $t_1$  must be a generating  $b$ -tuple of  $S$ , so  $(s_i, t_1)$  (being a generating  $d$ -tuple of  $S$ ) is  $A$ -conjugate to the  $j$ -th column of  $E$  for some  $\tau_1 < j \leq \tau$ . This means that the  $j$ -th column of  $E$  is

$$\begin{pmatrix} s_i \\ t_1^\alpha \end{pmatrix}$$

for some  $\alpha \in A$ . It follows that if we replace the first column of  $E$  with

$$\begin{pmatrix} s_i^{\alpha^{-1}} \\ t_1 \end{pmatrix}$$

and the  $j$ -th column with

$$\begin{pmatrix} s_1 \\ t_1^\alpha \end{pmatrix}$$

we get a matrix  $E^*$ , corresponding to an edge in  $\Gamma_{a,b}^*(S^\tau)$  between  $z$  and an element  $\bar{y}_i$ , obtained from  $\bar{x}$  by replacing the first column with  $s_i^{\alpha^{-1}}$  and the  $j$ th-column with  $s_1$ . □

**Theorem 4.4.** *Let  $\tau = \tau_{a+b}(S)$ . Then the graph  $\Gamma_{a,b}^*(S^\tau)$  is connected.*

*Proof.* Clearly the star  $\Gamma_{0,b}^*(S^\tau)$  is connected and  $\Gamma_{1,1}^*(S^\tau)$  is connected by [11, Thm. 3.1], so we may assume  $0 < a \leq b$  and  $(a, b) \neq (1, 1)$ . In particular  $b \geq 2$ . Let  $W_a$  be the set of the elements of  $V_a$  which belong to the connected component of  $\Gamma_{a,b}^*(S^\tau)$  which contains the vertex  $\bar{x}$ . The set  $W_a$  is a block for the action of  $K$  on  $V_a$ . In particular the setwise stabilizer  $H$  of  $W_a$  in  $K$  contains the point stabilizer  $C = C_K(\bar{x}) = \prod_{1 \leq i \leq u} C_A(s_i) \wr \text{Sym}(\tau_i)$ . We identify  $K$  with  $A \wr \text{Sym}(\tau)$ : in particular every element  $k \in K$  can be written in the form  $k = (a_1, \dots, a_\tau)\sigma$  with  $a_i \in A$  and  $\sigma \in \text{Sym}(\tau)$  and the map  $\pi : k \mapsto \sigma$  is a group homomorphism from  $K$  to  $\text{Sym}(\tau)$ .

Since  $C \leq H$ , we have  $C^\pi = \prod_{1 \leq i \leq u} \text{Sym}(\tau_i) \leq H^\pi$ . The orbits of  $C^\pi$  are

$$\Omega_1 = \{1, \dots, \tau_1\}, \Omega_2 = \{\tau_1 + 1, \dots, \tau_1 + \tau_2\}, \dots, \Omega_u = \{\tau - \tau_u + 1, \dots, \tau\}.$$

Let  $j \in \{2, \dots, u\}$  and choose  $\bar{y}_j$  as in Lemma 4.3. It follows from Corollary 4.2 that  $\bar{y}_j = \bar{x}^{k_j}$  for some  $k_j \in K$ . In particular  $\bar{y}_j \in W_a \cap W_a^{k_j}$  so, since  $W_a$  is a block,  $W_a = W_a^{k_j}$  and  $k_j \in H$ . Let  $\sigma_j = k_j^\pi : \text{we have } \sigma_j = (1, i_j)$  with  $i_j \in \Omega_j$ . This means that

$$\text{Sym}(\tau) = \langle \sigma_2, \dots, \sigma_u, \text{Sym}(\tau_1), \dots, \text{Sym}(\tau_u) \rangle \leq \langle k_2, \dots, k_u, C \rangle^\pi \leq H^\pi,$$

hence  $H^\pi = \text{Sym}(\tau)$ . We identify  $S$  with  $\text{Inn}(S) \leq A$ . Let  $z \in A$  and consider  $k = (z, 1, \dots, 1) \in K$ . Clearly  $\bar{x}^k = \bar{x}$ , hence  $k \in H$ . But then  $H$  contains  $(z, 1, \dots, 1)$  for every  $z \in A$ : being  $H^\pi = \text{Sym}(\tau)$ , this implies that  $H = K$ .

Now we have  $V_a = \bar{x}^K = \bar{x}^H \leq W_a$ , hence  $W_a = V_a$  and  $\Gamma_{a,b}^*(S^\tau)$  is a connected graph. □

Let  $S = \text{SL}(2, 2^p)$  with  $p > 3$ . We are going to prove that

$$\lim_{p \rightarrow \infty} \text{diam}\left(\Gamma_{a,b}^*(S^{\tau_{a+b}(S)})\right) = \infty,$$

for every pair  $a, b$  of positive integer. Let  $q = 2^p$ . We have  $|S| = (q^2 - 1)q$  and  $A = \text{Aut}(S) = S \rtimes \langle \phi \rangle$  with  $\phi$  the Frobenius automorphism. Note that, since  $p \neq 3$ , then  $p$  does not divide  $|S|$ ; in particular  $\langle \phi \rangle$  is a Sylow  $p$ -subgroup of  $A$ . Given  $k = (u_1, \dots, u_\tau)\pi \in K \leq A \wr \text{Sym}(\tau)$ , let  $\sigma_k$  be the number of  $i \in \{1, \dots, \tau\}$  with  $u_i \notin S$ .

**Lemma 4.5.** *Let  $k \in K$ .*

1. *If  $k \in C$ , then*

$$\sigma_k \leq \begin{cases} 6^a \cdot \frac{|S|^b}{p} & \text{if } a \neq 1, \\ 3 \cdot \frac{|S|^{d-1}}{pq} & \text{otherwise.} \end{cases}$$

2. *If  $k \in D$ , then*

$$\sigma_k \leq \begin{cases} 6^b \cdot \frac{|S|^a}{p} & \text{if } b \neq 1, \\ 3 \cdot \frac{|S|^{d-1}}{pq} & \text{otherwise.} \end{cases}$$

*Proof.* It suffice to prove (1) (the argument for (2) is the same). Assume that  $s \in S$  has the property that  $|C_A(s)|$  is divisible by  $p$ . By the Sylow theorem,  $\phi \in C_A(s)^\alpha = C_A(s^\alpha)$  for some  $\alpha \in A$ . It follows that  $s^\alpha \in C_S(\phi) = \text{SL}(2, 2) \cong \text{Sym}(3)$ . In particular, exactly three of the representatives  $\eta_1, \dots, \eta_\nu$  for the  $A$ -orbits of  $S$  satisfy the condition that  $p$  divides  $|C_A(\eta_i)|$ . More precisely we may assume:

1.  $\eta_1 = 1$ ;
2.  $|\eta_2| = 2$  and  $|C_A(\eta_2)| = p \cdot q$ ;
3.  $|\eta_3| = 3$  and  $|C_A(\eta_3)| = p \cdot (q + 1)$ .

First assume  $a \neq 1$ . We order the elements  $s_1, \dots, s_l \in S^a$  in such a way that  $C_A(s_i) \not\subseteq S$  if and only if  $i \leq l$ . If  $i \leq l$  and  $s_i = (z_1, \dots, z_a)$ , then we may assume  $\{z_1, \dots, z_a\} \subseteq C_S(\phi) \cong \text{Sym}(3)$ . Hence

$$l \leq 6^a. \tag{4.1}$$

Moreover, if  $(s_i, t)$  and  $(s_i, t^*)$  are generating  $d$ -tuples for  $S$  which are not  $A$ -conjugate, then  $t$  and  $t^*$  belong to different orbits for the action of  $C_A(s_i)$  on  $S^b$ , so for  $i \in \{1, \dots, l\}$

$$\tau_i \leq \frac{|S|^b}{|C_A(s_i)|} \leq \frac{|S|^b}{p} \quad \text{and} \quad \sigma_k \leq 6^a \cdot \frac{|S|^b}{p}. \tag{4.2}$$

The case  $a = 1$  follows with a similar argument, noticing that if  $i \leq l$ , then  $s_i \in \{\eta_1, \eta_2, \eta_3\}$  and that  $|C_A(\eta_j)| \leq |S|/pq$  for  $j \in \{1, 2, 3\}$ . □

**Theorem 4.6.** *Let  $S = \text{SL}(2, 2^p)$  with  $p > 3$ , assume that  $a \leq b$  are positive integers and let  $\tau = \tau_{a+b}(S)$ .*

1. *If  $a \neq 1$  and  $p$  is large enough, then*

$$\text{diam}\left(\Gamma_{a,b}^*(S^\tau)\right) \geq \frac{|S|^{a-1}}{2 \cdot 6^a} - 1.$$

2. *If  $a = 1$  and  $p$  is large enough, then*

$$\text{diam}\left(\Gamma_{1,b}^*(S^\tau)\right) \geq \frac{2^p}{6} - 1.$$

*Proof.* By [22], the probability  $P(S)$  of generating a simple group with 2 elements tends to 1 as  $|S|$  tends to infinity. In particular if  $p$  is large enough, then

$$\tau \geq \frac{|S|^d}{2|A|} = \frac{|S|^{d-1}}{2p}. \tag{4.3}$$

Case 1:  $a \neq 1$ . First assume  $a \neq b$ . Let  $(\bar{x}, \bar{y})$  be an edge of  $\Gamma_{a,b}(S^\tau)$  with  $\bar{x} \in S^{a\tau}$  and  $\bar{y} \in S^{b\tau}$  and let  $C = C_K(\bar{x})$ ,  $D = C_K(\bar{y})$ . We may identify the elements of  $V_a$  with the right cosets of  $C$  in  $K$  and the elements of  $V_b$  with the right cosets of  $D$  in  $K$ : there is an edge between  $Cx$  and  $Dy$  if and only if  $Cx \cap Dy \neq \emptyset$ . Assume in particular that our graph contains the path  $(Cx_1, Dy, Cx_2)$ : there exist  $c_1, c_2 \in C$  and  $d_1, d_2 \in D$  with

$$c_1x_1 = d_1y, \quad c_2x_2 = d_2y,$$

hence

$$x_2 = c_2^{-1}d_2y = c_2^{-1}d_2d_1^{-1}c_1x_1 \in CDCx_1.$$

More generally if there exists a path of length  $2r$  from  $Cx_1$  to  $Cx_2$  then

$$x_2 \in \underbrace{CDC \dots DC}_{r \text{ terms}} x_1.$$

Assume  $\text{diam}(\Gamma_{a,b}(S^\tau)) \geq 2r$ . By the previous paragraph

$$K = C \underbrace{DC \dots DC}_{r \text{ terms}},$$

and in particular there exist  $c_0, \dots, c_r \in C$  and  $d_0, \dots, d_{r-1} \in D$  such that

$$(\phi, \dots, \phi) = c_0 d_0 \dots c_{r-1} d_{r-1} c_r. \quad (4.4)$$

However, by Lemma 4.5

$$c_0 d_0 \dots c_{r-1} d_{r-1} c_r = (w_1, \dots, w_\tau) \rho$$

with  $w_i \notin S$  for at most

$$(r+1) \left( 6^a \cdot \frac{|S|^b}{p} \right) + r \left( 6^b \cdot \frac{|S|^a}{p} \right) \leq \frac{(2r+1) \cdot 6^a \cdot |S|^b}{p}$$

choices of  $i$ . Hence

$$\frac{(2r+1) \cdot 6^a \cdot |S|^b}{p} \geq \tau \geq \frac{|S|^{d-1}}{2 \cdot p}$$

and this implies

$$2r+1 \geq \frac{|S|^{a-1}}{2 \cdot 6^a}.$$

Now assume  $a = b$ . We may choose  $\bar{x} = (x_1, \dots, x_\tau)$  and  $\bar{y} = (y_1, \dots, y_\tau)$  with the property: if  $(x_i, y_i)$  and  $(y_i, x_i)$  are not  $A$ -conjugate, then there exist  $i^*$  such that  $x_{i^*} = y_i$  and  $y_{i^*} = x_i$ . Now let  $J = \{i \mid (x_i, y_i) \text{ and } (y_i, x_i) \text{ are not } A\text{-conjugate}\}$ . We have already noticed that there exists  $k = (a_1, \dots, a_\tau) \sigma \in K$  such that  $\bar{y} = \bar{x}^k$  and  $\bar{x} = \bar{y}^k$ . Clearly  $k$  can be chosen so that:

1. if  $i \in J$ , then  $i\sigma = i^*$  and  $a_i = 1$ ;
2. if  $i \notin J$ , then  $i\sigma = i$  and  $(x_i, y_i)^{a_i} = (y_i, x_i)$ .

If  $i \notin J$ , then  $x_i^{a_i^2} = x_i$  and  $y_i^{a_i^2} = y_i$ , hence, since  $S = \langle x_i, y_i \rangle$ , we have  $a_i^2 = 1$ . Since 2 does not divide  $|A/S| = p$ , it must be  $a_i \in S$ . We can conclude that  $a_i \in S$  for each  $i \in \{1, \dots, \tau\}$ . By [11, Cor. 5.2], there exist  $r \leq \text{diam}(\Gamma_{a,a}^*(S^\tau))$  and  $c_i = (u_{i1}, \dots, u_{i\tau}) \sigma_i \in C$  such that  $(\phi, \dots, \phi) = c_0 k c_1 \dots k c_r$ . On the other hand, by Lemma 4.5

$$c_0 k c_1 \dots k c_r = (w_1, \dots, w_\tau) \rho$$

with  $w_i \notin S$  for at most

$$(r+1) \cdot 6^a \cdot \frac{|S|^a}{p}$$

choices of  $i$ . Hence

$$(r+1) \cdot 6^a \cdot \frac{|S|^a}{p} \geq \tau \geq \frac{|S|^{d-1}}{2p}$$

and this implies

$$r+1 \geq \frac{|S|^{a-1}}{2 \cdot 6^a}.$$

Case 2:  $\mathbf{a} = \mathbf{1}$ . The case  $a = b = 1$  is considered in [12, Thm. 5.4] so we may assume  $a \neq b$ . The argument is similar to the one used in Case 1. Indeed again we can say that  $(\phi, \dots, \phi) = c_0 d_0 \dots c_{r-1} d_{r-1} c_r$  and so, by Lemma 4.5,

$$(r+1) \left( 3 \cdot \frac{|S|^{d-1}}{pq} \right) + r \left( 6^{d-1} \cdot \frac{|S|}{p} \right) \leq \frac{(2r+1) \cdot 3 \cdot |S|^{d-1}}{pq}$$

choices of  $i$ . Hence

$$\frac{(2r+1) \cdot 3 \cdot |S|^{d-1}}{pq} \geq \tau \geq \frac{|S|^{d-1}}{2 \cdot p}$$

and this implies

$$2r+1 \geq \frac{q}{6}.$$

□

We conclude this section with the following application of Theorem 4.4.

**Theorem 4.7.** *Assume that  $G$  is a direct product of finite non-abelian simple groups and let  $a, b$  nonnegative integers with  $a + b \geq d(G)$ . Then  $\Gamma_{a,b}^*(G)$  is connected.*

*Proof.* Assume  $G = S_1^{n_1} \times \dots \times S_r^{n_r}$  with  $S_1, \dots, S_r$  pairwise non isomorphic nonabelian finite simple groups. We prove our statement by induction on  $r$ . Let  $d = a + b$  and let  $\tau_i = \tau_d(S_i)$ . We have that  $S_i^{n_i}$  is an epimorphic image of  $S_i^{\tau_i}$ , so it follows from Theorem 4.4 and Lemma 2.8 that  $\Gamma_{a,b}^*(S_i^{n_i})$  is connected. In particular our statement is true if  $r = 1$ . Suppose that  $r \geq 2$  and let  $\Gamma_1 = \Gamma_{a,b}^*(S_1^{n_1} \times \dots \times S_{r-1}^{n_{r-1}})$  and  $\Gamma_2 = \Gamma_{a,b}^*(S_r^{n_r})$ . By induction  $\Gamma_1$  and  $\Gamma_2$  are connected graphs. If  $a = b$ , then  $\Gamma_1$  and  $\Gamma_2$  are not bipartite, so by [35, Thm. 1] we conclude that  $\Gamma_{a,b}^*(G) = \Gamma_1 \times \Gamma_2$  is connected. Suppose  $a \neq b$ . In this case  $\Gamma_1$  is a connected bipartite graph, with two parts  $A \subseteq (S_1^{n_1} \times \dots \times S_{r-1}^{n_{r-1}})^a$  and  $B \subseteq (S_1^{n_1} \times \dots \times S_{r-1}^{n_{r-1}})^b$  and  $\Gamma_2$  is a connected bipartite graph, with two parts  $C \subseteq (S_r^{n_r})^a$  and  $D \subseteq (S_r^{n_r})^b$ . It can be easily seen that  $\Gamma_{a,b}^*(G)$  can be identified with the subgraph of  $\Gamma_1 \times \Gamma_2$  induced by  $(A \times C) \cup (B \times D)$ . Now let  $(x, y)$  be an edge of  $\Gamma_1$ , with  $x \in A$  and  $y \in B$ . The subgraph of  $\Gamma_{a,b}^*(G)$  induced by  $(\{x\} \times C) \cup (\{y\} \times D)$  is isomorphic to  $\Gamma_2$ , hence is connected. Since this is true for every edge of  $\Gamma_1$  and  $\Gamma_1$  is connected, we immediately conclude that  $\Gamma_{a,b}^*(G)$  is connected as well. □

## 5 | PROPERTIES OF $G$ THAT CAN BE RECOGNIZED FROM THE GRAPHS $\Gamma_{a,b}^*(G)$

In this section we will denote by  $\Lambda(G)$  the collection of all the connected components of the graphs  $\Gamma_{a,b}(G)$ , for all the possible choices of  $a \leq b$  in  $\mathbb{N}$ . However, for each of this graph we don't assume to know from which choice of  $a, b$  it arises. In particular  $\Lambda(G)$  contains lot of graphs just consisting of only one vertex and with no edge. From these graphs we cannot recover any information, so we may restrict our attention to the collection  $\Lambda^*(G)$  of all the connected components of the graphs  $\Gamma_{a,b}^*(G)$ , for all  $a, b \in \mathbb{N}$ . We deal with two questions:

Question 5.1. Given a graph  $\Gamma \in \Lambda^*(G)$ , can we determine the integers  $a, b$  such that  $\Gamma$  is a connected component of  $\Gamma_{a,b}^*(G)$ ?

Question 5.2. Which information on  $G$  can be deduced from the knowledge of  $\Lambda^*(G)$ ?

We already noticed that a graph  $\Gamma \in \Lambda^*(G)$  can contain loops: we will denote by  $\tilde{\Gamma}$  the graph obtained from  $\Gamma$  by deleting the loops. In this way we produce a new collection  $\tilde{\Lambda}^*(G)$  of graphs. In this section we will also prove that  $\Lambda^*(G)$  can be reconstructed from the knowledge of  $\tilde{\Lambda}^*(G)$  which means that we do not lose information if we remove all the loops from the graphs (see Corollary 5.7).

Since a bipartite graph has a unique partition (up to switching the two sets) if and only if it is connected, Corollary 2.7 tell us that when  $a \neq b$ , each connected component  $\Gamma_{a,b}^*(G)$  is a bipartite graph whose unique partition has two parts, namely  $V_a$  and  $V_b$ , corresponding to elements of  $G^a$  and  $G^b$  respectively. Note that if  $a + b = d(G)$  and  $G$  is not soluble, then we do not know whether  $\Gamma_{a,b}^*(G)$  is connected.

The generating properties of cyclic groups are quite peculiar and exceptional from many points of view. As a result of this, one is immediately able to decide from the knowledge of  $\Lambda^*(G)$  whether  $G$  is cyclic.

**Proposition 5.3.** *From the knowledge of either  $\Lambda^*(G)$  or  $\tilde{\Lambda}^*(G)$  we may recognize whether  $G$  is cyclic, and, when  $G$  is cyclic, determine  $|G|$ .*

*Proof.* The case  $G = 1$  is uniquely characterized by the fact that  $\Lambda^*(G)$ , and consequently  $\tilde{\Lambda}^*(G)$ , contains infinitely many copies of the complete graph  $K_2$ : indeed  $\Gamma_{0,b}^*(G) \cong K_2$  for every positive integer  $b$ . Now assume that  $G$  is a non-trivial cyclic group: only in this case  $\Lambda^*(G)$  contains two stars (corresponding to  $\Gamma_{0,1}^*(G)$  and  $\Gamma_{0,2}^*(G)$ , respectively) with the property that there is no bipartite graph in  $\Lambda^*(G)$  with the same number of edges. If we imagine removing the loops, then we can still recognize the cyclic groups since we have two situations: either we see only two stars of type  $K_{1,1}$ , or we still see two stars with no bipartite graphs with the same number of edges. In the former case the group is  $C_2$  and in the latter one it is any other cyclic group of order greater than two. Once we know that  $G$  is a non-trivial cyclic group, we consider all the stars in  $\Lambda^*(G)$  sorted by the increasing number of leaves  $u_i$ , for  $i \geq 0$ : they correspond to the graphs  $\Gamma_{0,i+1}^*(G)$ . Note that  $\Gamma_{1,2}^*(G)$  is the only bipartite graph in  $\Lambda^*(G)$  with  $u_2$  edges and  $|G|$  is the cardinality of the smallest set in the partition of  $\Gamma_{1,2}^*(G)$ .  $\square$

Since we can identify the cyclic groups, from now on we assume, without loss of generality, that  $d(G) \geq 2$ . By Lemma 2.3 a graph  $\Gamma \in \Lambda^*(G)$  is either bipartite or contains a 3-cycle. There is a loop around a vertex  $x = (x_1, \dots, x_r)$  if and only if  $G = \langle x_1, \dots, x_r \rangle$  and  $\Gamma$  is not bipartite. In this case  $x$  is adjacent to all other vertices of  $\Gamma_{r,r}^*(G)$ . We want to analyse in which other cases a vertex of a graph in  $\Lambda^*(G)$  can have this last property.

**Theorem 5.4.** *Let  $G$  be a non-cyclic finite group. Assume that there exists  $\Gamma \in \Lambda^*(G)$  containing a 3-cycle and a vertex  $x$  which is adjacent to all the other vertices of  $\Gamma$ . Then either there is a loop in  $\Gamma$  around  $x$  or  $d(G) = 2$  and  $G$  is isomorphic either to the Klein group or to the dihedral group  $D_p$ , for some odd prime  $p$ .*

*Proof.* Assume that  $x = (x_1, x_2, \dots, x_r)$ . Since  $\Gamma$  contains a 3-cycle, it is a connected component of  $\Gamma_{r,r}^*(G)$ , for  $r \geq 1$ . In particular there exists  $y = (y_1, \dots, y_r)$  such that  $G = \langle x_1, x_2, \dots, x_r, y_1, \dots, y_r \rangle$ .

First assume  $r \geq 2$ . If  $x$  has at least two distinct entries, say  $x_i$  and  $x_j$  with  $i < j$ , then

$$x^* = (x_1, \dots, x_j, \dots, x_i, \dots, x_r)$$

is also a vertex of  $\Gamma$ , since it is adjacent to  $y$ . Hence  $x$  is adjacent to  $x^*$  and  $G$  is generated by the  $r$  elements  $x_1, \dots, x_r$ : in this case we have a loop around  $x$ . If  $x_1 = \dots = x_r$  and  $x_1 \neq 1$ , then again  $x^* = (x_1, 1, \dots, 1)$  is adjacent to  $y$  and consequently to  $x$  and this implies that  $G$  is cyclic. Finally if  $x = (1, \dots, 1)$ , then any tuple of type  $(z, 1, \dots, 1)$ , with  $z \in G$ , is adjacent to  $y$  and consequently to  $x$  and again  $G$  is cyclic.

Now assume  $r = 1$ . As a consequence  $\Gamma$  is a connected component of the generating graph  $\Gamma_{1,1}^*(G)$  and  $d(G) = 2$ . Since  $x$  is a non-isolated vertex, there exists  $y$  such that  $G = \langle x, y \rangle$ . First of all observe that  $x$  must have order 2, otherwise also  $x^{-1}$  would be adjacent to  $y$  and, in particular to  $x$ , contradicting the fact that  $G$  is 2-generated. If  $x$  is not the unique involution in  $\Gamma$ , then  $G$  is generated by two involutions and so it is a dihedral group. Otherwise, since the element  $x^y$  also generates  $G$  with  $y$ , we have  $x = x^y$ . Therefore  $x$  belongs to  $x \in Z(\langle x, y \rangle) = Z(G)$  and, consequently,  $G$  is abelian and  $\Gamma = \Gamma_{1,1}^*(G)$ . Since  $G$  is not cyclic, we must have that  $\langle x \rangle$  has a cyclic complement, say  $H$ , in  $G$  and that  $|H|$  is even: but in this case  $H$  contains an involution, say  $z$ , such that  $xz$  is a non-isolated involution, contradicting the uniqueness of  $x$ .

We have so proved that  $G$  is isomorphic to the semidirect product of  $\langle x \rangle \simeq C_2$  with  $\langle t \rangle \simeq C_m$ , for some integer  $m$ . If a prime  $p$  divides  $m$ , then the element  $xt^p$  generates  $G$  together with  $t$ . This implies  $x = xt^p$  (otherwise  $xt^p$  would be adjacent to  $x$ ). Hence  $t^p = 1$  and  $n = p$ . If  $p = 2$ , then  $G \cong C_2 \times C_2$ , otherwise  $G \cong D_p$ .

Note, conversely, that if either  $G \cong C_2 \times C_2$  or  $G \cong D_p$ , then any involution of  $G$  is adjacent to all the other vertices of  $\Gamma_{1,1}(G)$ .  $\square$

**Corollary 5.5.** *Let  $G$  be any non-cyclic group which is isomorphic neither to  $C_2 \times C_2$  nor to  $D_p$ , for any odd prime  $p$ , and let  $\Gamma \in \Lambda^*(G)$ . There is a loop around a vertex  $x$  of  $\Gamma$  if and only if  $\Gamma$  contains a 3-cycle and  $x$  is adjacent to all the other vertices of  $\Gamma$ .*

Due to the exceptional behavior of the loops in  $\Gamma \in \Lambda^*(G)$  when  $G$  is either  $C_2 \times C_2$  or  $D_{2p}$ , it is useful to be able to determine from  $\Lambda^*(G)$  whether or not we are in one of these cases.

**Proposition 5.6.** *From the knowledge of either  $\Lambda^*(G)$  or  $\tilde{\Lambda}^*(G)$  we may recognize whether  $G$  is isomorphic either to the Klein group or to the dihedral group  $D_p$  for some odd prime  $p$ , and, in that case, determine  $|G|$ .*

*Proof.* It follows from Theorem 5.4 that  $G$  is either the Klein group or the dihedral group  $D_p$  if and only if every  $\Gamma \in \Lambda^*(G)$  containing a 3-cycle contains also a vertex adjacent to all the other vertices. In this case  $G$  is the Klein group if and only if  $\Lambda^*(G)$  contains the complete graph  $K_3$ . If  $K_3$  is not in  $\Lambda^*(G)$ , then  $G \cong D_p$  for some  $p$ . In order to determine  $p$ , we consider all the stars in  $\Lambda^*(G)$ : they correspond to  $\Gamma_{0,r}^*(G) \cong K_{1,\phi_G(r)}$ , with  $r \geq 2$ : so we may determine  $\phi_G(2) = \min_{r \geq 2} \phi_G(r)$ . On the other hand

$$\phi_G(2) = 4p^2 \left(1 - \frac{1}{4}\right) \left(1 - \frac{1}{p}\right),$$

which is an injective function on  $p$ , whenever  $p \geq 2$ . Hence by the knowledge of  $\phi_G(2)$  we recognize  $p$  and consequently  $|G|$ .  $\square$

**Corollary 5.7.** *Let  $G$  be a finite group. We may determine  $\Lambda^*(G)$  from the knowledge of  $\tilde{\Lambda}^*(G)$ .*

*Proof.* By Propositions 5.3 and 5.6 we may assume that  $G$  is neither cyclic nor dihedral of order  $2p$ . But then, by Corollary 5.5, assuming that we have removed all loops in advance, we can easily recognize which vertices have a loop around and put them back.  $\square$

**Definition 5.8.** Given  $\Gamma \in \Lambda^*(G)$ , let  $e(\Gamma)$  be the number of edges, excluding the loops,  $l(\Gamma)$  be the number of loops and set  $\nu(\Gamma) = 2e(\Gamma) + l(\Gamma)$  if  $\Gamma$  contains a 3-cycle,  $\nu(\Gamma) = e(\Gamma)$  otherwise.

**Proposition 5.9.** *Let  $G$  be a finite group. We may determine  $d(G)$  from the knowledge of  $\Lambda^*(G)$ .*

*Proof.* By Proposition 5.3 we may assume  $d = d(G) \geq 2$ . We consider all the stars in  $\Lambda^*(G)$  sorted by the increasing number of leaves  $u_i$ , for  $i \geq 0$ : they corresponds to the graph  $\Gamma_{0,d(G)+i}^*(G)$  for  $i \in \mathbb{N}$ . If  $\Gamma$  is a connected component of  $\Gamma_{a,b}^*(G)$  and  $a + b = d$ , then  $\nu(\Gamma) \leq u_0$ . On the other hand if  $a + b > d$ , then, by Corollary 2.7,  $\Gamma = \Gamma_{a,b}^*(G)$  is connected and  $\nu(\Gamma) = u_{a+b-d}$ . Let  $\Omega$  be the subfamily of  $\Lambda^*(G)$  consisting of the graphs  $\Gamma$  with  $\nu(\Gamma) = u_1$ . Depending on the parity of  $d + 1$  we have the following two situations:

1.  $\Omega$  contains  $\Gamma_{0,d+1}^*(G) \cong K_{0,u_1}$ , other bipartite  $x = \left\lfloor \frac{d-1}{2} \right\rfloor$  graphs not isomorphic to the star  $K_{0,u_1}$  and no graph containing a 3-cycle.
2.  $\Omega$  contains  $\Gamma_{0,d+1}^*(G) \cong K_{0,u_1}$ , other bipartite  $x = \left\lfloor \frac{d-1}{2} \right\rfloor$  graphs not isomorphic to the star  $K_{0,u_1}$  and exactly one graph containing a 3-cycle.

In the former case  $d + 1$  is odd and  $d = 2x$ . In the second case  $d + 1$  is even and  $d = 2x + 1$ .  $\square$

The following definition is useful to deal with Question 5.1.

**Definition 5.10.** Let  $G \neq 1$  be a finite group and let  $\Gamma \in \Lambda^*(G)$ . We say that  $\Gamma$  has level  $t$  if there exist  $a, b$  such that  $t = a + b$  and  $\Gamma$  is a connected component of  $\Gamma_{a,b}^*(G)$ .

The following lemma says that this is a good definition.

**Lemma 5.11.** *Let  $G \neq 1$  be a finite group. If  $\Gamma \in \Lambda^*(G)$ , then the level of  $\Gamma$  is uniquely determined.*

*Proof.* Put  $d = d(G)$  and assume that  $\Gamma_{0,d+i}^*(G)$  has  $u_i$  leaves for  $i \geq 0$ . Let  $\Gamma \in \Lambda^*(G)$ . If  $\nu(\Gamma) \leq u_0$ , then  $\Gamma$  has level  $d$ . Otherwise  $\nu(\Gamma) = u_i$  for some positive integer  $i$  and  $\Gamma$  has level  $d + i$ .  $\square$

**Lemma 5.12.** *Let  $G \neq 1$  be a finite group. Let  $a + b > d(G)$  and let  $V_a$  and  $V_b$  be the two parts of the bipartite graph  $\Gamma_{a,b}^*(G)$  corresponding to elements of  $G^a$  and  $G^b$ , respectively. If  $a < b$  then  $|V_a| < |V_b|$ .*

*Proof.* For any  $x = (x_1, \dots, x_a) \in V_a$ , there exists a generating  $(a + b)$ -tuple  $z = (z_1, \dots, z_{a+b})$  for  $G$  such that  $x_i = z_i$  for  $1 \leq i \leq a$ . We have  $y = (z_1, \dots, z_b) \in V_b$ , since its entries generate  $G$  together with the  $a$ -tuple  $(z_{b+1}, \dots, z_{a+b})$ . We define an injective map  $\phi : V_a \rightarrow V_b$  by setting  $\phi(x) = y$ . Assume by contradiction that  $\phi$  is surjective. It can be easily seen that this implies that every  $x \in V_a$  has degree 1 in  $\Gamma_{a,b}^*(G)$ . By Lemma 2.4 this is possible only when  $G = 1$ .  $\square$

Now we can give the following answer to Question 5.1.

**Proposition 5.13.** *Let  $G \neq 1$  be a finite group. If  $\Gamma \in \Lambda^*(G)$  has level at least  $d(G) + 1$ , then there exists a uniquely determined pair  $a \leq b$  such that  $\Gamma \cong \Gamma_{a,b}^*(G)$ .*

*Proof.* Let  $d = d(G)$  and assume that  $\Gamma$  has level  $r = d + i$  with  $i \geq 1$ . We easily recognize the star  $\Gamma_{0,r}^*(G)$  and, if  $r$  is even,  $\Gamma_{r/2,r/2}^*(G)$ , which is the unique graph, at that level, containing a 3-cycle. Now we want to sort somehow all the bipartite graphs  $\Gamma_{a,b}^*(G)$ , with  $1 \leq a < r/2$  and  $b = r - a$ . In this case  $\Gamma_{a,b}^*(G)$  is a bipartite graph with the unique partition given by the two sets  $V_a$  and  $V_b$ , and, as we have seen in the previous lemma,  $|V_a| < |V_b|$ . We claim that  $|V_a| < |V_{a+1}|$  whenever  $2a < r - 2$ . It is enough to construct  $\phi : V_a \rightarrow V_{a+1}$  which is injective but not surjective. For any  $x = (x_1, \dots, x_a) \in V_a$ , there exists  $y = (y_1, \dots, y_b) \in V_b$  such that  $G = \langle x_1, \dots, x_a, y_1, \dots, y_b \rangle$ . Therefore the  $(a + 1)$ -tuple  $(x_1, \dots, x_a, y_1)$  is obviously an element of  $V_{a+1}$ , since it generates  $G$  with the tuple  $(y_2, \dots, y_b)$ . We set  $\phi(x) = (x_1, \dots, x_a, y_1)$ . The map  $\phi$  defined in this way is clearly injective. As in the proof of the previous lemma, it can be easily seen that  $\phi$  is not surjective.  $\square$

The remaining part of this section is devoted to collect answers to Question 5.2.

**Proposition 5.14.** *Let  $G$  be a finite group. We may determine  $|G|$  from the knowledge of  $\Lambda^*(G)$ .*

*Proof.* By Proposition 5.9 we may determine  $d = d(G)$ . Moreover by Lemma 5.11 and Proposition 5.13, we may identify the graph  $\Gamma = \Gamma_{1,d}^*(G)$ , which is a bipartite graph with a unique partition in two parts. The two parts are  $V_1$  and  $V_d$ . By Lemma 5.12  $|G| = |V_1| < |V_d|$ .  $\square$

An immediate consequence of the results in this section is:

**Theorem 5.15.** *Let  $G$  be a finite group. We may determine  $P_G(s)$  from the knowledge of  $\Lambda^*(G)$ .*

**Corollary 5.16.** *Let  $G$  be a finite group. From the knowledge of  $\Lambda^*(G)$  we may determine whether  $G$  is soluble, whether  $G$  is supersoluble and, for every prime power  $n$ , the number of maximal subgroups of  $G$  of index  $n$ .*

*Proof.* If we know  $\Lambda^*(G)$ , then we know  $P_G(s)$  and so we may deduce whether  $G$  is soluble ([13, Thm. 5]), whether  $G$  is supersoluble ([14, Cor. 6]) and for every prime power  $n$ , the number of maximal subgroups of  $G$  of index  $n$  ([14, Cor. 18]).  $\square$

Although several properties of  $G$  can be recognized by the knowledge of the coefficients of the Dirichlet polynomial  $P_G(s)$ , this is not always the case. For example we cannot deduce from  $P_G(s)$  whether  $G$  is nilpotent. Consider for example  $G_1 = C_6 \times C_3$  and  $G_2 = \text{Sym}(3) \times C_3$ . It turns out that

$$P_{G_1}(s) = P_{G_2}(s) = \left(1 - \frac{1}{2^s}\right) \left(1 - \frac{1}{3^s}\right) \left(1 - \frac{3}{3^s}\right).$$

We want to show that nevertheless  $\Lambda^*(G)$  encodes enough information to decide whether  $G$  is nilpotent. Before proving this result, we need an auxiliary lemma.

**Lemma 5.17.** *Let  $\alpha = (a_1, \dots, a_r)$ ,  $\beta = (b_1, \dots, b_s)$  be two sequences of prime integers, with  $a_1 \leq \dots \leq a_r$  and  $b_1 \leq \dots \leq b_s$ . If*

$$\prod_i \left(1 - \frac{1}{a_i}\right) = \prod_j \left(1 - \frac{1}{b_j}\right),$$

then  $\alpha = \beta$ .

*Proof.* By induction on  $r + s$ . We have

$$\prod_i a_i \prod_j (b_j - 1) = \prod_i (a_i - 1) \prod_j b_j. \quad (5.1)$$

Let  $p = \max\{a_1, \dots, a_r, b_1, \dots, b_s\}$ ,  $r^* = \max\{i \mid a_i \neq p\}$ ,  $s^* = \max\{j \mid b_j \neq p\}$ . Since  $p$  does not divide  $a_i - 1$ ,  $b_j - 1$ , divides  $a_i$  if and only if  $i > r^*$  and divides  $b_j$  if and only if  $j > s^*$ , we deduce that  $r - r^*$  is the multiplicity of  $p$  in the left term of (5.1) and  $s - s^*$  is the multiplicity of  $p$  in the right term of (5.1). In particular  $r - r^* = s - s^*$  and  $a_{r^*+1} = \dots = a_r = b_{s^*+1} = \dots = b_s = p$ . But then

$$\prod_{i \leq r^*} \left(1 - \frac{1}{a_i}\right) = \prod_{j \leq s^*} \left(1 - \frac{1}{b_j}\right),$$

and we conclude by induction. □

**Theorem 5.18.** *Let  $G$  be a finite nilpotent group. If  $H$  is a finite group and  $\Lambda^*(H) = \Lambda^*(G)$ , then  $H$  is nilpotent.*

*Proof.* Let  $G$  be a finite nilpotent group. For every  $p \in \pi(G)$  let  $d_p = d(P)$  where  $P$  is a Sylow  $p$ -subgroup of  $G$ . For every nonnegative integer  $\delta$  consider the Dirichlet polynomials

$$Q_{p,\delta}(s) = \prod_{0 \leq i \leq \delta-1} \left(1 - \frac{p^i}{p^s}\right), \quad \tilde{Q}_{p,\delta}(s) = \prod_{1 \leq i \leq \delta} \left(1 - \frac{p^i}{p^s}\right).$$

We have

$$P_G(s) = \prod_{p \in \pi(G)} Q_{p,d_p}(s).$$

Since  $\Lambda^*(H) = \Lambda^*(G)$ , it follows from Theorem 5.15 and Corollary 5.16 that  $P_H(s) = P_G(s)$  and that  $H$  is a finite supersoluble group with  $d(H) = d(G) = d$ . By Lemma 5.11 and Proposition 5.13 in  $\Lambda^*(H) = \Lambda^*(G)$  we may uniquely identify the graph  $\Delta = \Gamma_{1,d}^*(G) = \Gamma_{1,d}^*(H)$ : it is a bipartite graph whose partition has two parts  $V_1$  and  $V_d$  such that  $|V_1| = |G| = |H|$ . We are going to use the knowledge of the degrees of the vertices of  $V_d$  to deduce that  $H$  must be nilpotent.

Since  $H$  is supersoluble,  $\bar{H} = H / \text{Frat}(H)$  can be written in the form

$$\bar{H} = H / \text{Frat}(H) \cong \left(W_1^{r_1} \times \dots \times W_t^{r_t}\right) \rtimes X,$$

where  $X$  is abelian,  $|W_i| = p_i$  for a suitable prime  $p_i$  and each  $W_i$  is non-central. For every  $p \in \pi(X)$ , let  $\delta_p = d(Q)$ , where  $Q$  is a Sylow  $p$ -subgroup of  $H$ . By [18, Satz 2], we have

$$P_H(s) = \prod_{p \in \pi(X)} Q_{p,\delta_p}(s) \prod_{1 \leq i \leq t} \tilde{Q}_{p_i,r_i}(s).$$

Let  $\pi = \{p_1, \dots, p_t\}$ . Since  $P_G(s) = P_H(s)$ , by [14, Lemma 16] we deduce that the primes  $p_1, \dots, p_t$  are pairwise distinct,  $d_{p_i} = r_i + 1$  and  $\delta_{p_i} = 1$  for  $1 \leq i \leq t$ . Moreover  $d_p = \delta_p$  if  $p \in \pi(G) \setminus \pi$ .

If  $\omega = (g_1, \dots, g_d) \in G^d$  corresponds to a non-isolated vertex of  $\Delta$ , then the degree of  $\omega$  in  $\Delta$  is  $\delta_\omega = |G|P_G(S, 1)$ , with  $S = \langle g_1, \dots, g_d \rangle$  (here we denote by  $P_G(S, 1)$  the probability that a randomly chosen element of  $G$  generates  $G$  together with  $S$ ). Notice that  $P_G(S, 1) = P_G(S \text{ Frat}(G), 1) = P_{G/S \text{ Frat}(G)}(1)$  so there exists a subset  $\pi_\omega$  of  $\pi(G)$  such that

$$\delta_\omega = |G| \prod_{p \in \pi_\omega} \left(1 - \frac{1}{p}\right) = |V_1| \prod_{p \in \pi_\omega} \left(1 - \frac{1}{p}\right). \tag{5.2}$$

In order to conclude that  $H$  is nilpotent, it suffices to prove that  $\pi = \{p_1, \dots, p_t\} = \emptyset$ . Assume, by contradiction,  $\pi \neq \emptyset$ , and let  $q = p_1$ . We have  $X = Y \times Q$ , where  $Q$ , the Sylow  $q$ -subgroup of  $X$ , is cyclic. Let  $K$  be a subgroup of  $H$  such that

$$\bar{K} = K / \text{Frat}(H) = (W_1^{r_1-1} \times \dots \times W_t^{r_t}) \rtimes Y.$$

It can be easily seen that  $d(\bar{K}) \leq d(\bar{H}) = d$ . So there exists  $(h_1, \dots, h_d) \in H^d$  such that  $K = \langle h_1, \dots, h_d \rangle \text{Frat} H$ . Let  $\alpha = (h_1, \dots, h_d)$ . We have

$$\delta_\alpha = |H|P_H(\langle h_1, \dots, h_d \rangle, 1) = |V_1|P_{\bar{H}}(\bar{K}, 1) = |V_1| \left(1 - \frac{1}{p_1}\right)^2.$$

We deduce from (5.2) that there exists  $\pi \subseteq \pi(G)$  such that

$$\prod_{p \in \pi} \left(1 - \frac{1}{p}\right) = \left(1 - \frac{1}{p_1}\right)^2,$$

in contradiction with Lemma 5.17. □

Another piece of information that we cannot recover from the knowledge of  $|G|$  and  $P_G(s)$  is the order of  $\text{Frat}(G)$ . For example consider

$$G_1 = \langle x, y \mid x^5 = 1, y^4 = 1, x^y = x^2 \rangle$$

and

$$G_2 = \langle x, y \mid x^5 = 1, y^4 = 1, x^y = x^4 \rangle.$$

We have  $|G_1| = |G_2| = 20$  and

$$P_{G_1}(s) = P_{G_2}(s) = \left(1 - \frac{1}{2^s}\right) \left(1 - \frac{5}{5^s}\right)$$

however  $\text{Frat}(G_1) = 1$  and  $\text{Frat}(G_2) = \langle x^2 \rangle$ . This motivates the following proposition.

**Proposition 5.19.** *Let  $G$  be a finite group. We may determine  $|\text{Frat}(G)|$  from the knowledge of  $\Lambda^*(G)$ .*

*Proof.* Since  $G$  is finite, there exists  $\delta \in \mathbb{N}$  such that  $d(H) \leq \delta$  for every  $H \leq G$ . Let  $t \geq \delta$  and consider the graph  $\Gamma_{1,t}^*(G)$  (we may identify this graph by Lemma 5.11 and Proposition 5.13). In  $V_t$  there are some vertices (the ones corresponding to the generating  $t$ -uples of  $G$ ) that are adjacent to all the vertices in  $V_1$ . We remove these vertices and the edges starting from them. We obtain a new bipartite graph in which some vertices of  $V_1$  are isolated: let  $\Omega_t$  be the set of these vertices. Notice that  $(g) \in \Omega_t$  if and only  $\langle g, x_1, \dots, x_t \rangle \neq G$  whenever  $\langle x_1, \dots, x_t \rangle \neq G$ . Since  $d(H) \leq t$  for every  $H \leq G$ , we deduce that  $(g) \in \Omega_t$  if and only  $\langle g, H \rangle \neq G$  whenever  $H \neq G$ . In other words  $(g) \in \Omega_t$  if and only if  $g \in \text{Frat}(G)$ . We conclude that we may determine  $n = |\text{Frat}(G)|$  from the fact that  $|\Omega_t| = n$  if  $t$  is sufficiently large. □

**Corollary 5.20.** *Let  $G$  be a finite non-abelian simple group. If  $H$  is finite group and  $\Lambda^*(H) = \Lambda^*(G)$ , then  $H \cong G$ .*

*Proof.* By Theorem 5.15  $P_G(s) = P_H(s)$ , hence  $H/\text{Frat}(H) \cong G$  by [32, Thm. 1]. Moreover, by the previous proposition,  $|\text{Frat}(H)| = |\text{Frat}(G)| = 1$ , hence  $H \cong G$ .  $\square$

**Lemma 5.21.** *Assume that  $\Lambda^*(G)$  is known and let  $a, b$  be a pair of nonnegative integers. If either  $a + b > d(G)$  or  $a + b = d(G)$  and  $G$  is soluble, then we may determine the graph  $\Gamma_{a,b}(G/\text{Frat}(G))$ .*

*Proof.* Let  $f = |\text{Frat}(G)|$ . Under our assumptions we know that  $\Gamma_{a,b}^*(G)$  is connected. First assume  $a \neq b$ :  $\Gamma_{a,b}^*(G)$  is a bipartite graph with  $|V_a| + |V_b|$  vertices, while  $\Gamma_{a,b}(G)$  has  $|G|^a + |G|^b$  vertices. In particular,  $\Gamma_{a,b}(G)$  is uniquely determined from  $\Gamma_{a,b}^*(G)$ : it suffices to add  $|G|^a - |V_a| + |G|^b - |V_b|$  isolated vertices. Similarly, if  $a = b$ , then  $\Gamma_{a,b}(G)$  can be obtained from  $\Gamma_{a,b}^*(G)$  by adding  $|G|^a - |V|$  isolated vertices to the set  $V$  of the vertices of  $\Gamma_{a,b}^*(G)$ . In both cases we note that if  $\langle x_1, \dots, x_a, y_1, \dots, y_b \rangle = G$ , then  $\langle x_1\alpha_1, \dots, x_a\alpha_a, y_1\beta_1, \dots, y_b\beta_b \rangle = G$  for every  $\alpha_i, \beta_j \in \text{Frat}(G)$ . We may consider the following equivalent relations in  $\Gamma_{a,b}(G)$ :  $\omega_1 \sim_1 \omega_2$  if and only if  $\omega_1$  and  $\omega_2$  have the same neighbourhood in the graph;  $\omega_1 = (x_1, \dots, x_\gamma) \sim_2 (y_1, \dots, y_\gamma)$ , with  $\gamma \in \{a, b\}$ , if and only if for any  $j$  there exists  $f_j \in \text{Frat}(G)$  with  $y_j = x_j f_j$ . For every vertex  $x = (x_1, \dots, x_\gamma)$  of  $\Gamma_{a,b}(G)$ , the equivalence class  $\Omega_x = [x]_{\sim_1}$  is the disjoint union of  $|\Omega_x|/f^\gamma \sim_2$ -equivalence classes: we obtain  $\Gamma_{a,b}(G/\text{Frat}(G))$  from  $\Gamma_{a,b}(G)$ , by deleting from every equivalence class  $\Omega_x$  precisely  $|\Omega_x|(1 - 1/f^\gamma)$  vertices.  $\square$

By the previous results, at least in the case of finite soluble groups, the knowledge of  $\Lambda^*(G)$  is equivalent to the knowledge of  $\Lambda^*(G/\text{Frat}(G))$  and  $|\text{Frat}(G)|$ .

From what we proved in this section, a question naturally arises:

**Question 5.22.** Assume that  $G$  is a (soluble) group with  $\text{Frat}(G) = 1$ . Is  $G$  uniquely determined from  $\Lambda^*(G)$ ?

The answer is negative. Indeed, consider the following example. Let  $C_1 = \langle x_1 \rangle$  and  $C_2 = \langle x_2 \rangle$  be two cyclic groups of order 5 and let  $V_1 = \langle a_1, b_1 \rangle$ ,  $V_2 = \langle a_2, b_2 \rangle$  be two vector space over the field with 11 elements. We define an action of  $C_1$  on  $V_1$  in which  $x_1$  takes  $a_1$  to  $3a_1$  and  $b_1$  to  $4b_1$ , and an action of  $C_2$  on  $V_2$  in which  $x_2$  takes  $a_2$  to  $3a_2$  and  $b_2$  to  $5b_2$ . The semidirect products  $G_1 = V_1 \rtimes C_1$  and  $G_2 = V_2 \rtimes C_2$  are both of order 605. It is easy to see that  $G_1 \not\cong G_2$ , since every element of  $C_1$  has determinant 1 while this is not true for  $C_2$ . For  $j = 1, 2$  let  $W_{1,j} = \langle a_j \rangle$ ,  $W_{2,j} = \langle b_j \rangle$  and let  $\pi_{i,j}$  be the projection  $G_j \rightarrow G_j/W_{i,j}$ . We now construct a bijection  $\tau : G_1 \rightarrow G_2$  in the following way:

- we set  $\tau((\alpha a_1 + \beta b_1)x_1^\gamma) = (\alpha a_2 + \beta b_2)x_2^\gamma$  if  $\gamma = 0, 1 \pmod{5}$ ;
- let  $g = (\alpha a_1 + \beta b_1)x_1^\gamma$  with  $\gamma \not\equiv 0 \pmod{5}$ . There exist  $\alpha^*, \beta^*$  (depending on  $\alpha, \beta, \gamma$ ) such that  $g = ((\alpha^* a_1 + \beta^* b_1)x_1)^\gamma$ . We set  $g^\tau = ((\alpha^* a_2 + \beta^* b_2)x_2)^\gamma$ .

For  $i \in \{1, 2\}$ ,  $\tau$  induces a bijection  $\tau_i : G_1/W_{i,1} \rightarrow G_2/W_{i,2}$ . We have

$$\langle g^{\tau\pi_{i,2}} \rangle = \langle g^{\pi_{i,1}} \rangle^{\tau_i}. \quad (5.3)$$

We claim that  $\langle g_1, \dots, g_d \rangle = G_1$  if and only if  $\langle g_1^\tau, \dots, g_d^\tau \rangle = G_2$ . Clearly this claim implies that  $\tau$  induces a graph isomorphism between  $\Gamma_{a,b}(G_1)$  and  $\Gamma_{a,b}(G_2)$  for every pair  $a, b$  of nonnegative integers. To prove the claim notice that  $\langle y_1, \dots, y_d \rangle = G_j$  if and only if  $\langle y_1^{\pi_{i,j}}, \dots, y_d^{\pi_{i,j}} \rangle = G_j/W_{i,j}$  for  $i \in \{1, 2\}$  and that  $\langle y_1^{\pi_{i,j}}, \dots, y_d^{\pi_{i,j}} \rangle = G_j/W_{i,j}$  if and only if there exist  $k_1, k_2$  with  $\langle y_{k_1}^{\pi_{i,j}} \rangle \neq \langle y_{k_2}^{\pi_{i,j}} \rangle$ . So assume  $\langle g_1, \dots, g_d \rangle = G_1$  and fix  $i \in \{1, 2\}$ . There exist  $k_1, k_2$  with  $\langle g_{k_1}^{\pi_{i,1}} \rangle \neq \langle g_{k_2}^{\pi_{i,1}} \rangle$ . It follows from (5.3) that

$$\langle g_{k_1}^{\tau\pi_{i,2}} \rangle = \langle g_{k_1}^{\pi_{i,1}} \rangle^{\tau_i} \neq \langle g_{k_2}^{\pi_{i,1}} \rangle^{\tau_i} = \langle g_{k_2}^{\tau\pi_{i,2}} \rangle,$$

and so we conclude  $\langle g_1^\tau, \dots, g_d^\tau \rangle = G_2$ .

We conclude by observing that most of the arguments in this section use only part of the information given by the family  $\Lambda^*(G)$ . In particular it seems a natural question to ask whether a smaller family of graphs can efficiently encode

the generating property of  $G$ . In some crucial steps of the proofs of our results (for example in the proof of Theorem 5.18 and Proposition 5.19) a decisive role is played by the graphs  $\Gamma_{1,t}^*(G)$ . So a good candidate to consider seems to be the family  $\Delta_1^*(G)$  of the connected components of the graphs  $\Gamma_{1,t}^*(G)$  for  $t \in \mathbb{N}$ . We assume  $\Delta_1^*(G) = \{\Delta_k\}_{k \in \mathbb{N}}$ , where the graphs are enumerated in such a way that  $\nu(\Delta_k) \leq \nu(\Delta_{k+1})$  for every  $k \in \mathbb{N}$ .

**Theorem 5.23.** *Assume that the family  $\Delta_1^*(G)$  is known. We may determine  $|G|$ ,  $d(G)$ ,  $P_G(s)$  and  $|\text{Frat}(G)|$ . Moreover, we may recognize whether or not  $G$  is soluble, supersoluble, nilpotent.*

*Proof.* If  $G$  is cyclic, then  $\Delta_0 = \Gamma_{1,0}^*(G)$  is a non-trivial connected graph containing a vertex of degree 1, while, by Lemma 2.4, if  $G$  is not cyclic none of the graphs  $\{\Delta_k\}_{k \in \mathbb{N}}$  can contain a vertex of degree 1. So we may recognize from  $\Delta_1^*(G)$  whether  $G$  is cyclic. Therefore, from now on we will assume that  $G$  is not cyclic.

Let  $d = d(G)$ . There exists  $\tau \in \mathbb{N}$  such that  $\Delta_0, \dots, \Delta_\tau$  are the connected components of  $\Gamma_{1,d-1}^*(G)$ . By Corollary 2.7, for  $k > \tau$  we have  $\Delta_k = \Gamma_{1,d+k-\tau-1}^*(G)$ . We need to recognize  $\tau$ . Notice that if  $k > \tau$ , then  $\Delta_k$  is a bipartite graph with one of the two parts consisting precisely of  $|G|$  vertices and the second part containing a subset of  $\phi_G(d+k-\tau-1)$  vertices connected to all the vertices of the first part. We claim that  $\Delta_k$  does not behave in this way whenever  $k \leq \tau$ . If  $d = 2$ , then none of the connected components of  $\Gamma_{1,1}(G)$  is bipartite. So we may assume  $d \neq 2$ . Assume by contradiction that there exists a connected component of  $\Gamma_{1,d-1}^*(G)$ , say  $\Delta$ , which is a bipartite graph with two parts  $A$  and  $B$  such that  $|A| = |G|$  and at least one vertex in  $B$  is connected to all the vertices in  $A$ . Since (1) is an isolated vertex of  $\Gamma_{1,d-1}(G)$ , it must be  $A \subseteq G^{d-1}$  and  $B \subseteq G$ . Let  $(x) \in B$  be a vertex connected to all the vertices of  $A$ . Fix  $(g_1, \dots, g_{d-1}) \in A$ . Since

$$\langle x, g_1, \dots, g_{d-1} \rangle = \langle x, g_1x, g_2, \dots, g_{d-1} \rangle = \langle g_1, g_1x, g_2, \dots, g_{d-1} \rangle = \langle g_1, x, g_2, \dots, g_{d-1} \rangle$$

we have  $(x, g_2, \dots, g_{d-1}) \in A$ , hence  $(x)$  and  $(x, g_2, \dots, g_{d-1})$  are adjacent, but this would imply  $G = \langle x, g_2, \dots, g_{d-1} \rangle$ , hence  $d(G) \leq d - 1$ , a contradiction.

Once  $\tau$  has been determined, we have that  $|G|$  is the cardinality of the smaller part in the bipartite graph  $\Delta_k$ , for any choice of  $k > \tau$ . Alternatively, we may notice that

$$\lim_{k \rightarrow \infty} \frac{\nu(\Delta_{k+1})}{\nu(\Delta_k)} = \lim_{k \rightarrow \infty} \frac{\phi_G(d+k-\tau+1)}{\phi_G(d+k-\tau)} = |G|.$$

We can also determine  $d(G)$ , since  $\nu(\Delta_k) = \phi_G(d+k-\tau) \sim |G|^{d+k-\tau}$  if  $k$  is large enough and so

$$d = \lim_{k \rightarrow \infty} \log_{|G|}(\nu(\Delta_k)) - k + \tau.$$

But now we know  $P_G(k)$  for every positive integer  $k \neq d(G)$  and this is enough to determine the Dirichlet polynomial  $P_G(s)$ . In particular we may recognize whether  $G$  is soluble, supersoluble, nilpotent (for this we repeat the argument in Theorem 5.18). Moreover we may determine  $|\text{Frat}(G)|$  (same proof as Proposition 5.19).  $\square$

## 6 | GENERALIZING SOME DEFINITIONS AND RESULTS FROM [7]

The following equivalence relation  $\equiv_m$  was introduced in [8, Sect. 2]: two elements are equivalent if each can be substituted for the other in any generating set for  $G$ . By [8, Prop. 2.2],  $x \equiv_m y$  if and only if  $x$  and  $y$  lie in exactly the same maximal subgroups of  $G$ . We then refine this to a sequence  $\equiv_m^{(r)}$  of equivalence relations by saying that, for any positive integer  $r$ ,  $x \equiv_m^{(r)} y$  if and only if

$$(\forall z_1, \dots, z_{r-1} \in G) \quad ((\langle x, z_1, \dots, z_{r-1} \rangle = G) \Leftrightarrow (\langle y, z_1, \dots, z_{r-1} \rangle = G)).$$

Notice that  $x \equiv_m^{(r)} y$  if and only if  $(x)$  and  $(y)$  have the same neighbours in the graph  $\Gamma_{1,r-1}(G)$ . In particular,  $\Gamma_{1,r-1}(G)$  determines the number of classes for the equivalence relation  $\equiv_m^{(r)}$  and the sizes of these classes. The relations  $\equiv_m^{(r)}$  become finer as  $r$  increases. We define a group invariant  $\psi(G)$  to be the value of  $r$  at which the relations  $\equiv_m^{(r)}$  stabilise to  $\equiv_m$ . If

$G$  is soluble then  $\psi(G) \in \{d(G), d(G) + 1\}$  (see [8, Cor. 2.12]). Furthermore, in general  $d(G) \leq \psi(G) \leq d(G) + 5$  (see [8, Cor. 2.13]), however no example is known of a finite group  $G$  for which  $\psi(G) > d(G) + 1$ . For  $r \geq \psi(G)$ , we have that  $(x)$  and  $(y)$  have the same neighbours in the graph  $\Gamma_{1,r-1}(G)$  if and only if  $x \equiv_m y$ . In particular from the knowledge of the family of graphs  $\{\Gamma_{1,r-1}(G)\}_{r \in \mathbb{N}}$  we may determine the precise value of  $\psi(G)$ .

Given a subset  $X$  of a finite group  $G$ , we will denote by  $d_X(G)$  the smallest cardinality of a set of elements of  $G$  generating  $G$  together with the elements of  $X$ . In [8, Def. 2.15] the following notion is also introduced: a finite group  $G$  is efficiently generated if for all  $x \in G$ ,  $d_{\{x\}}(G) = d(G)$  implies that  $x \in \text{Frat}(G)$ .

**Proposition 6.1.** *Assume that the family  $\Delta_1^*(G) = \{\Gamma_{1,r-1}^*(G)\}_{r \in \mathbb{N}}$  is known. We may deduce whether  $G$  is or not efficiently generated.*

*Proof.* First, by Theorem 5.23, we may determine  $d(G)$ ,  $|G|$  and  $|\text{Frat}(G)|$ . Moreover, inside the family  $\Delta_1^*(G)$ , we may identify the connected components of  $\Gamma_{1,d(G)-1}^*(G)$  and consequently we may count how many of the vertices of  $\Gamma_{1,d(G)-1}(G)$  corresponding to 1-tuples are isolated. Let  $\omega$  be the number of these vertices:  $G$  is efficiently generated if and only if  $|\text{Frat}(G)| = \omega$ . □

**Corollary 6.2.** *Assume that the family  $\Delta_1^*(G)$  is known. If  $G$  is soluble, then we may determine  $\psi(G)$ .*

*Proof.* Assume that  $G$  is a finite soluble group. By [8, Cor. 2.20],  $\psi(G) = d(G)$  if  $G$  is efficiently generated,  $\psi(G) = d(G) + 1$  otherwise, so the conclusion follows immediately from the previous proposition. □

Generalizing a definition given in [8] for 2-generator groups, we say that a finite  $G$  has non-zero spread if  $(g)$  is not isolated in the graph  $\Gamma_{1,d(G)-1}(G)$  for every  $g \neq 1$ . Moreover we define an equivalence relation  $\equiv_\Gamma$  on the elements of  $G$  by the rule  $x \equiv_\Gamma y$  if  $(x)$  and  $(y)$  have the same set of neighbours in the graph  $\Gamma_{1,d(G)-1}(G)$ . The following statements generalize [8, Prop. 4.5] and [8, Thm. 4.6] and can be easily proved.

**Proposition 6.3.** *Let  $G$  be a finite group. Then the relations  $\equiv_\Gamma$  and  $\equiv_m^{(d)}$  on  $G$  coincide; hence  $\equiv_m$  is a refinement of  $\equiv_\Gamma$ , and is equal to  $\equiv_\Gamma$  if and only if  $\psi(G) \leq d$ .*

**Theorem 6.4.** *Let  $G$  be a finite group with  $d(G) = d$ .*

- (1)  $G$  has non-zero spread if and only if  $G$  is efficiently generated and has trivial Frattini subgroup.
- (2) If  $G$  is soluble and has non-zero spread, then  $\psi(G) = d$ .

Assume that  $G$  is a finite group with non-zero spread and let  $d = d(G)$ . If  $N$  is a non-trivial normal subgroup of  $G$ , then  $d(G/N) < d$  (otherwise we would have  $d_{\{y\}}(G) = d$  for every  $y \in N$ ). So  $G$  has the following property:

(★) every proper quotient can be generated by  $d - 1$  elements, but  $G$  cannot.

When  $d(G) = 2$ , groups with non-zero spread are also called  $\frac{3}{2}$ -generated. In [3], Breuer, Guralnick and Kantor make the following remarkable conjecture: a finite group is  $\frac{3}{2}$ -generated if and only if every proper quotient is cyclic. In our terminology we could propose the following more general conjecture:

**Conjecture 6.5.** *A finite group  $G$  has non-zero spread if and only if  $G$  satisfies the property (★).*

The groups with this property (★) have been studied in [13]. By [13, Thm. 1.4 and Thm. 2.7], there exists a monolithic primitive group  $L$  and a positive integer  $t$  such that  $G \cong L_t$  and  $d(L_{t-1}) < d(L_t)$  (setting  $L_0 = L/\text{soc}(L)$ ). This motivates the following question:

Question 6.6. Let  $L$  be a finite monolithic primitive group and  $t \in \mathbb{N}$ . Assume that  $G \cong L_t$  and  $d(L_{t-1}) < d(L_t)$ . Does  $G$  have non-zero spread?

The remain part of this section will give an affirmative answer to the previous question.

First assume that  $N = \text{soc } L$  is nonabelian. If  $t = 1$  then by [29, Thm. 1.1]  $d = d(G) = d(L) = \max(d(L/N), 2) \leq \max(d - 1, 2)$ , hence  $d = 2$  and Question 6.6 has an affirmative answer by Theorem 1 in [7]. Suppose  $t \neq 1$  (and consequently  $d \neq 2$ ) and let  $x = (l, ln_2, \dots, ln_t)$ , with  $l \in L$ ,  $n_i \in N$ , be a non-identity element of  $G = L_t$ . Since  $d(L_{t-1}) < d$ , there exist  $y_1 = (l_1, l_1 m_{1,2}, \dots, l_1 m_{1,t-1})$ ,  $\dots$ ,  $y_{d-1} = (l_{d-1}, l_{d-1} m_{d-1,2}, \dots, l_{d-1} m_{d-1,t-1})$  such that  $L_{t-1} = \langle y_1, \dots, y_{d-1} \rangle$ . This is equivalent to say that the rows of the matrix

$$A := \begin{pmatrix} l_1 & l_2 & \dots & l_{d-1} \\ l_1 m_{1,2} & l_2 m_{2,2} & \dots & l_{d-1} m_{d-1,2} \\ \vdots & \vdots & \dots & \vdots \\ l_1 m_{1,t-1} & l_2 m_{2,t-1} & \dots & l_{d-1} m_{d-1,t-1} \end{pmatrix}$$

are generating  $(d - 1)$ -tuples of  $L$  which belong to distinct orbits with respect to the conjugacy action of  $C = C_{\text{Aut } L}(L/N)$ . Since  $x$  is a non-identity element of  $G$ , there exist  $i \in \{2, \dots, t\}$  and  $n$  in  $N$  such that  $l^n \neq ln_i$ . Up to reordering, we may assume  $i = t$ . Let  $\tilde{y}_1 = (l_1, l_1 m_{1,2}, \dots, l_1 m_{1,t-1}, l_1^n)$ ,  $\dots$ ,  $\tilde{y}_{d-1} = (l_{d-1}, l_{d-1} m_{d-1,2}, \dots, l_{d-1} m_{d-1,t-1}, l_{d-1}^n)$ . We claim that  $L_t = \langle \tilde{y}_1, \dots, \tilde{y}_{d-1}, x \rangle$ . This is equivalent to say that the rows of the matrix

$$\tilde{A} := \begin{pmatrix} l_1 & l_2 & \dots & l_{d-1} & l \\ l_1 m_{1,2} & l_2 m_{2,2} & \dots & l_{d-1} m_{d-1,2} & ln_2 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ l_1 m_{1,t-1} & l_2 m_{2,t-1} & \dots & l_{d-1} m_{d-1,t-1} & ln_{t-1} \\ l_1^n & l_2^n & \dots & l_{d-1}^n & ln_t \end{pmatrix}$$

are generating  $d$ -tuples of  $L$  which belong to distinct orbits with respect to the conjugacy action of  $C = C_{\text{Aut } L}(L/N)$ . The way in which  $A$  has been constructed ensures that the first  $t - 1$  rows of  $\tilde{A}$  satisfy the requested properties. We have only to prove that the last row cannot be  $C$ -conjugate to one of the first  $t - 1$  rows. Suppose  $i \in \{2, \dots, t - 1\}$ : since  $(l_1, l_2, \dots, l_{d-1})$  and  $(l_1 m_{1,i}, l_2 m_{2,i}, \dots, l_{d-1} m_{d-1,i})$  are not  $C$ -conjugate and  $n \in C$  we deduce that also  $(l_1^n, l_2^n, \dots, l_{d-1}^n, ln_t)$  and  $(l_1 m_{1,i}, l_2 m_{2,i}, \dots, l_{d-1} m_{d-1,i}, ln_i)$  are not  $C$ -conjugate. Finally assume by contradiction that there exists  $\gamma \in C$  with  $(l_1^n, \dots, l_{d-1}^n, ln_t) = (l_1, \dots, l_{d-1}, l)^\gamma$ . Since  $\langle l_1, \dots, l_{d-1} \rangle = L$ , we have  $C_C(l_1, \dots, l_{d-1}) = 1$ , hence  $n = \gamma$  and consequently  $ln_t = l^n$ , a contradiction. So we have proved that Question 6.6 has an affirmative answer when  $\text{soc}(L)$  is nonabelian.

Now assume that  $N = \text{soc } L$  is abelian. We have  $L = N \rtimes H$ , where  $H$  is an irreducible subgroup of  $\text{Aut}(N)$  and  $d(H) = d(L/N) \leq d - 1$ . As usual, let  $F = \text{End}_H N$ ,  $q = |F|$ ,  $n = \dim_F(N)$ ,  $m = \dim_F(\text{Der}(H, N))$ . Let  $\delta_1, \dots, \delta_m$  be a basis of  $\text{Der}(H, N)$  as an  $F$ -vector space. For each  $h \in H$  consider the matrix  $A_h \in M_{m \times n}(F)$  defined by setting

$$A_h := \begin{pmatrix} \delta_1(h) \\ \vdots \\ \delta_m(h) \end{pmatrix}.$$

The following is an immediate consequence of [26, Prop. 5].

**Lemma 6.7.** *Suppose that  $H = \langle h_1, \dots, h_k \rangle$  and let  $u$  be a positive integer. Let  $w_i = (w_{i,1}, \dots, w_{i,u}) \in N^t$  with  $1 \leq i \leq k$  and let*

$$B_i = \begin{pmatrix} w_{i,1} \\ \vdots \\ w_{i,u} \end{pmatrix} \in M_{t \times n}(F).$$

*The following are equivalent.*

1.  $L_t = N^t \rtimes H = \langle h_1 w_1, \dots, h_k w_k \rangle$ ;

$$2. \operatorname{rank} \begin{pmatrix} A_{h_1} & \cdots & A_{h_k} \\ B_1 & \cdots & B_k \end{pmatrix} = m + t.$$

In particular,  $d(L_t) \leq k$  if and only if  $m + t \leq kn$ .

In our case  $d(G) = d(L_t) = d$  but  $d(L_{t-1}) \leq d - 1$ , since  $L_{t-1}$  is a proper epimorphic image of  $L_t$  : by the previous lemma we must have  $m + t - 1 = (d - 1)n$  i.e.,

$$t = (d - 1)n - m + 1.$$

Now assume that  $x := h(v_1, \dots, v_t)$  is a non-identity element of  $L_t$ . Fix  $h_1, \dots, h_{d-1}$  such that  $H = \langle h_1, \dots, h_{d-1} \rangle$ . There exist  $\tilde{w}_i \in N^{t-1}$ , for  $1 \leq i \leq d - 1$ , such that  $L_{t-1} = \langle h_1 \tilde{w}_1, \dots, h_{d-1} \tilde{w}_{d-1} \rangle$ , in other words

$$\det \begin{pmatrix} A_{h_1} & \cdots & A_{h_{d-1}} \\ \tilde{B}_1 & \cdots & \tilde{B}_{d-1} \end{pmatrix} \neq 0. \quad (6.1)$$

We claim that there exist  $u_1, \dots, u_{d-1} \in N$  such that

$$L_t = \langle h(v_1, \dots, v_t), h_1(\tilde{w}_1, u_1), \dots, h_{d-1}(\tilde{w}_{d-1}, u_{d-1}) \rangle. \quad (6.2)$$

Set

$$\tilde{B} = \begin{pmatrix} v_1 \\ \vdots \\ v_{t-1} \end{pmatrix}.$$

By Lemma 6.7, (6.2) is equivalent to

$$\operatorname{rank} \begin{pmatrix} A_h & A_{h_1} & \cdots & A_{h_{d-1}} \\ \tilde{B} & \tilde{B}_1 & \cdots & \tilde{B}_{d-1} \\ v_t & u_1 & \cdots & u_{d-1} \end{pmatrix} = (d - 1)n + 1 = m + t. \quad (6.3)$$

Since  $x \neq 1$ , we have

$$X := \begin{pmatrix} A_h \\ \tilde{B} \\ v_t \end{pmatrix} \neq 0.$$

In particular, at least one column of  $X$  is a non-zero element of  $M_{m+t,1}(F)$ . Let us write such a column in the form

$$Y = \begin{pmatrix} C \\ \gamma \end{pmatrix}$$

with  $C \in M_{m+t-1,1}(F)$  and  $\gamma \in F$ . Let

$$Z := \begin{pmatrix} A_{h_1} & \cdots & A_{h_{d-1}} \\ \tilde{B}_1 & \cdots & \tilde{B}_{d-1} \end{pmatrix}.$$

By (6.1),  $C$  is a linear combination of the columns of  $Z$ . If  $\gamma \neq 0$ , then

$$\det \begin{pmatrix} C & Z \\ \gamma & 0 \end{pmatrix} \neq 0,$$

so we are done if we choose  $u_1 = \dots = u_{d-1} = 0$ . If  $\gamma = 0$ , then  $C$  is a non-zero matrix, so, denoting by  $Z_i$  the  $i$ -th column of  $Z$ , there exists  $(0, \dots, 0) \neq (\lambda_1, \dots, \lambda_{(d-1)n}) \in F^{(d-1)n}$  such that  $\sum_i \lambda_i Z_i = C$ . Choose  $(\alpha_1, \dots, \alpha_{(d-1)n}) \in F^{(d-1)n}$  such that  $\sum_i \lambda_i \alpha_i \neq 0$ . If we choose

$$u_1 = (\alpha_1, \dots, \alpha_n), u_2 = (\alpha_{n+1}, \dots, \alpha_{2n}), \dots, u_{d-1} = (\alpha_{(d-2)n+1}, \dots, \alpha_{(d-1)n}),$$

then

$$\det \begin{pmatrix} C & & Z \\ 0 & u_1 & \dots & u_{d-1} \end{pmatrix} \neq 0.$$

Summarizing we proved:

**Proposition 6.8.** *The answer to Question 6.6 is affirmative. As a consequence Conjecture 6.5 is true.*

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