

Cross-wired lamplighter groups and linearity of automata groups

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ABSTRACT. We consider the two generalizations of lamplighter groups: automata groups generated by Cayley machines and cross-wired lamplighter groups. For a finite step two nilpotent group with central squares, we study its associated Cayley machine and give a presentation of the corresponding automata group. We show the automata group is a cross-wired lamplighter group and does not embed in the wreath product of a finite group with a torsion free group. For a subfamily of such finite step two nilpotent groups, we prove that their associated automata groups are linear.

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1. Introduction

The so called lamplighter group is a popular object of study. It is defined as a restricted wreath product $\mathbb{Z}_2 \wr \mathbb{Z}$, namely a semi-direct product $(\oplus_{\mathbb{Z}} \mathbb{Z}_2) \rtimes \mathbb{Z}$ with the action of \mathbb{Z} on $\oplus_{\mathbb{Z}} \mathbb{Z}_2$ by shifts, where \mathbb{Z} denotes integers and \mathbb{Z}_2 denotes $\mathbb{Z}/2\mathbb{Z}$. It is an infinitely presented 2-generated group.

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It is step-2 solvable and has exponential growth. In general, a lamplighter group could be a group of the form $F \wr \mathbb{Z}$ where F is some nontrivial finite group. There are two kinds of generalization of lamplighter groups: automata groups generated by Cayley machines [11, 17] and cross-wired lamplighter groups [2].

Grigorchuk and Żuk [11] showed that the lamplighter group $\mathbb{Z}_2 \wr \mathbb{Z}$ can be constructed as the automata group of a 2-state automaton. They used this automaton to compute the spectrum and spectral measure associated to random walks on the group, leading to a counterexample of the strong form of the Atiyah conjecture. Silva and Steinberg [17] showed that, for a finite abelian group F , the lamplighter group $F \wr \mathbb{Z}$ can be generated by a reset automaton, which they called the Cayley machine of the group F . Woryna [24] showed similar results for automata over changing alphabet. Pochon [15] first studied the Cayley machine of a finite nonabelian group around 2005. She gave the structure of the group generated by the Cayley machine of the Dihedral group of order 8. We extend her unpublished result to a large class of groups.

Theorem 1.1. *Let G be a finite step-2 nilpotent group. Assume the square of each element of G is central. Then the automata group generated by its Cayley machine has following presentation:*

$$\langle G, x \mid [g, x^{2n}hx^{-2n}] = [g, x^{2n-1}hx^{-2n+1}] = x^n[g, h]x^{-n}, g, h \in G, n \in \mathbb{Z} \rangle,$$

where the bracket denotes group commutator.

Thus, the theorem of Silva and Steinberg for the case of finite abelian groups is a corollary of Theorem 1.1. For a finite nonabelian group F , $F \wr \mathbb{Z}$ can not be an automata group. Indeed, for such finite group F , $F \wr \mathbb{Z}$ is residually finite if and only if F is abelian [12]. On the other hand, automata groups are always residually finite [10]. Silva and Steinberg conjectured that in the case of finite nonabelian group, the resulting automata group does not embed in the wreath product of a finite group with a torsion free group. In the appendix of [13], Kambites, Silva and Steinberg partially proved the conjecture. They showed for any finite nonabelian group that is not a direct product of an abelian group with a 2-group which is nilpotent of class 2, its associated automata group can not embed in a wreath product of a finite group with a torsion free group. We show the case when it contains a 2-group which is nilpotent of class 2.

Theorem 1.2. *Let G be a finite nonabelian group containing a 2-group that is nilpotent of class 2. Then the automata group generated by its Cayley machine does not embed in a wreath product of a finite group with a torsion free group.*

Combining results in the appendix of [13], we have:

Theorem 1.3. *The automata group associated to any finite nonabelian group does not embed in a wreath product of a finite group with a torsion free group.*

Some Cayley graphs of lamplighter groups are examples of Diestel–Leader graphs [3, 14, 22, 23]. Eskin, Fisher, and Whyte proved [6, 7, 8] that a finitely generated group is quasi-isometric to a lamplighter group if and only if it acts properly and cocompactly by isometries on some Diestel–Leader graph. In [2], Cornulier, Fisher and Kashyap studied quasi-isometric rigidity question of lamplighter groups by studying the cocompact lattices in the isometry group of the Diestel–Leader graphs. They showed that these lattices are not necessarily lamplighters and gave an algebraic characterization of them. They call these cocompact lattices *cross-wired lamplighter groups*. Lamplighter groups are examples of cross-wired lamplighters. It is suggested by L. Bartholdi that automata groups associated to some finite groups might provide other examples of cross-wired lamplighter groups. We show that the automata groups in Theorem 1.1 are cross-wired lamplighter groups.

Theorem 1.4. *The automata groups in Theorem 1.1 are cross-wired lamplighter groups.*

Cornulier, Fisher and Kashyap also give interesting examples that are not virtually lamplighter groups [2]. Let q be a prime power, and consider the Laurent polynomial ring $\mathbb{F}_q[t^{\pm 1}]$. Let \mathbf{H} be the Heisenberg group, consisting of unitriangular 3×3 matrices. Consider the action of \mathbb{Z} on $\mathbf{H}(\mathbb{F}_q[t^{\pm 1}])$ defined by the automorphism

$$\Phi : \begin{pmatrix} 1 & x & z \\ 0 & 1 & y \\ 0 & 0 & 1 \end{pmatrix} \mapsto \begin{pmatrix} 1 & tx & t^2z \\ 0 & 1 & ty \\ 0 & 0 & 1 \end{pmatrix}.$$

Then the group $\mathbf{H}(\mathbb{F}_q[t^{\pm 1}]) \rtimes_{\Phi} \mathbb{Z}$ is a cross-wired lamplighter group. This construction applies to other nilpotent groups over local field of positive characteristic with similar contraction \mathbb{Z} action. In the beginning, we believed that the automata groups in Theorem 1.1 might be totally different examples of cross-wired lamplighters from those examples above, or even nonlinear. By *linear* we mean the group can be embedded in a general linear group over some fields. As we know, many automata groups are nonlinear. The Grigorchuk groups [9, 5] are automata groups, of intermediate growth and hence nonlinear. But the lamplighter group $\mathbb{Z}_2 \wr \mathbb{Z}$ is linear over function fields [23]. So it is interesting to study the linearity/nonlinearity of those automata groups above. We find the following surprising. Let Q_8 be the quaternion group of order 8 and M_{2^n} be the Iwasawa/modular group of order 2^n , $n \geq 3$, $M_{2^n} = \langle a, b \mid a^{2^{n-1}} = b^2 = e, bab^{-1} = a^{2^{n-2}+1} \rangle$. The automata groups associated to Q_8 and M_{2^n} have index two subgroups behaving like above linear examples with diagonal contraction \mathbb{Z} action.

Theorem 1.5. *The automata groups associated to Q_8 and M_{2^n} are linear over $\mathbb{Z}_2[t^{\pm 1}]$.*

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2. Automata groups

2.1. Preliminaries: automata and Cayley machine. This subsection is similar with part of [13].

A *finite (Mealy) automaton* [4, 10, 13, 17] \mathcal{A} is a 4-tuple (Q, A, δ, λ) , where Q is a finite set of states, A is a finite alphabet, $\delta : Q \times A \rightarrow Q$ is the transition function and $\lambda : Q \times A \rightarrow A$ is the output function. We write qa for $\delta(q, a)$ and $q \circ a$ for $\lambda(q, a)$. Let A^* be the set of all words in letters of A . These functions extend to the free monoid A^* by

$$(2.1) \quad \begin{aligned} q(ab) &= (qa)b, \\ q \circ (ab) &= (q \circ a)(qa) \circ b. \end{aligned}$$

Let \mathcal{A}_q denote the *initial automaton* \mathcal{A} with designated start state $q \in Q$. There is a function $\mathcal{A}_q : A^* \rightarrow A^*$ given by $w \mapsto q \circ w$. This function is word length preserving and extends continuously [10] to the set of right infinite words A^ω via

$$(2.2) \quad \mathcal{A}_q(a_0 a_1 \cdots) = \lim_{n \rightarrow \infty} \mathcal{A}_q(a_0 \cdots a_n),$$

where A^ω is given the product topology and so homeomorphic to a Cantor set. If the function $\lambda_q : A \rightarrow A$, defined by $\lambda_q(a) = q \circ a$, is a permutation for each q , then \mathcal{A}_q is an isometry of A^ω with metric $d(u, v) = 1/(n+1)$, where n is the length of the longest common prefix of u and v [10]. In this case the automaton is called *invertible* and its *inverse* is denoted by \mathcal{A}^{-1} . Let $\Gamma = \mathcal{G}(\mathcal{A})$, \mathcal{A} invertible, be the group generated by all \mathcal{A}_q 's with $q \in Q$, and it is called the *automata group generated by automaton \mathcal{A}* .

Let T be the Cayley tree of A^* , then Γ acts on T by rooted tree automorphisms [10] via the action (2.1). The induced action on the boundary ∂T , the space of infinite directed paths from the root, is the action (2.2) of Γ on A^ω . Let $\text{Aut}(T)$ be the automorphism group of T . It is the iterated permutational wreath product of countably many copies of the left permutation group (S_A, A) [1, 10, 16], where S_A is the symmetric group on A . For a group $\Gamma = \mathcal{G}(\mathcal{A})$ generated by an automaton over A , one has the embedding

$$(2.3) \quad (\Gamma, A^\omega) \hookrightarrow (S_{|A|}, A) \wr (\Gamma, A^\omega).$$

Here we use the notation such that the wreath product of left permutation groups has a natural projection to its leftmost factor. Let $A = \{a_1, \dots, a_n\}$.

In wreath product coordinates, an element in the automata group can be represented as $\sigma(f_1, \dots, f_n)$, where $\sigma \in S_A$ and $f_1, \dots, f_n \in \Gamma$. It acts on the word $a_i x_2 x_3 \dots$ over A by the rule

$$\sigma(f_1, \dots, f_n)(a_i x_2 x_3 \dots) = \sigma(a_i) f_i(x_2 x_3 \dots).$$

Multiplication in wreath product coordinates is given by

$$(2.4) \quad \sigma(f_1, \dots, f_n) \tau(g_1, \dots, g_n) = \sigma \tau(f_{\tau(1)} g_1, \dots, f_{\tau(n)} g_n),$$

where $\sigma, \tau \in S_A \cong S_{\{1, 2, \dots, n\}}$ and $f_1, \dots, f_n, g_1, \dots, g_n \in \Gamma$. The map sends \mathcal{A}_q to the element with wreath product coordinates:

$$\mathcal{A}_q = \lambda_q(\mathcal{A}_{qa_1}, \dots, \mathcal{A}_{qa_n}).$$

Its inverse is given by

$$\mathcal{A}_q^{-1} = \lambda_q^{-1}(\mathcal{A}_{a_1}^{-1}, \dots, \mathcal{A}_{a_n}^{-1}).$$

Let $G = \{g_1 = 1, g_2, \dots, g_n\}$ be a nontrivial finite group. By the *Cayley machine* $\mathcal{C}(G)$ of G we mean the automaton with state G and alphabet G . Both the transition and the output functions are the group multiplication, i.e., at state g_0 on input g the machine goes to state $g_0 g$ and outputs $g_0 g$. The state function λ_g is just left translation by g and hence a permutation, so $\mathcal{C}(G)$ is invertible. The study of the automata group of the Cayley machine of a finite group was initiated by Silva and Steinberg [17].

An automaton is called a *reset automaton* if, for each $a \in A$, $|Qa| = 1$; that is, each input resets the automaton to a single state. Silva and Steinberg [17] showed that the inverse of a state $\mathcal{C}(G)_g, g \in G$, is computed by the corresponding state of the reset automaton $\mathcal{A}(G)$ with states and input alphabet G , where at state g_0 on input g the automaton goes to state g and outputs $g_0^{-1} g$. Therefore

$$\mathcal{C}(G)_g^{-1} = \mathcal{A}(G)_g, \quad \mathcal{G}(\mathcal{C}(G)) = \mathcal{G}(\mathcal{A}(G)).$$

In this case, from (2.3), we have the embedding

$$\mathcal{G}(\mathcal{A}(G)) \hookrightarrow (G, G) \wr (\mathcal{G}(\mathcal{A}(G)), G^\omega).$$

In wreath product coordinates,

$$(2.5) \quad \mathcal{A}(G)_g = g^{-1}(\mathcal{A}_{g_1}, \dots, \mathcal{A}_{g_n}).$$

Let $x := \mathcal{A}(G)_1 = \mathcal{C}(G)_1^{-1}$. Notice that [17], applying (2.4),

$$\begin{aligned} x \mathcal{A}(G)_g^{-1} &= x \mathcal{C}(G)_g \\ &= (\mathcal{A}_{g_1}, \dots, \mathcal{A}_{g_n}) g(\mathcal{C}(G)_{gg_1} \dots, \mathcal{C}(G)_{gg_n}) \\ &= g(\mathcal{A}_{gg_1} \mathcal{C}(G)_{gg_1}, \dots, \mathcal{A}_{gg_n} \mathcal{C}(G)_{gg_n}) \\ &= g(1, \dots, 1), \end{aligned}$$

so we can identify G with a subgroup of $\mathcal{G}(\mathcal{A}(G))$ via $g \leftrightarrow x \mathcal{A}(G)_g^{-1}$. Recall from [17] Equation 4.3 or by (2.5) that

$$x(f_0, f_1, f_2, f_3, f_4, \dots) = (f_0, f_0^{-1} f_1, f_1^{-1} f_2, f_2^{-1} f_3, f_3^{-1} f_4, \dots),$$

$x^{-1}(f_0, f_1, f_2, f_3, f_4, \dots) = (f_0, f_0f_1, f_0f_1f_2, f_0f_1f_2f_3, f_0f_1f_2f_3f_4, \dots)$,
 where $(f_0, f_1, f_2, f_3, f_4, \dots) \in G^\omega$.

Let

$$N := \langle x^n G x^{-n} \mid n \in \mathbb{Z} \rangle.$$

It is shown in [17] that x has infinite order, N is a locally finite group and $\mathcal{G}(\mathcal{A}(G)) = N \rtimes \langle x \rangle$, where x acts on N by conjugates. If G is abelian, it is shown in [17] that

$$\mathcal{G}(\mathcal{A}(G)) \cong G \wr \mathbb{Z}.$$

That is the automata group is a lamplighter group. If G is nonabelian and not of nilpotency class 2, then $\mathcal{G}(\mathcal{A}(G))$ does not embed in the wreath product of a finite group with a torsion free group.

The *depth* of an element $\gamma \in \Gamma$ is the least integer n (if it exists, otherwise infinity) so that γ only changes the first n letters of a word. For example, $g \in G$ has depth 1. Here is a useful lemma about depth:

Lemma 2.1. [17] *Let $\mathcal{A} = (Q, A, \delta, \lambda)$ be an invertible reset automaton and let $a = \mathcal{A}_p, b = \mathcal{A}_q$. Suppose $f \in \Gamma$ has depth n , then afb^{-1} has depth at most $n + 1$.*

Let

$$N_0 := \langle x^n G x^{-n} \mid n \geq 0 \rangle.$$

It is shown in [17] that $x^n g x^{-n}, g \neq 1$, has depth $n + 1$ and so N_0 consists of finitary automorphisms. It is shown in [17] that the elements of the form $\mathcal{A}(G)_g \in \Gamma$ with $g \in G$ generate a free subsemigroup of Γ .

2.2. Proof of Theorem 1.1. Let

$$G = \{g_1 = 1, g_2, \dots, g_k\}$$

be a group of nilpotency class two, for some $k \in \mathbb{N}$. Moreover we assume $g_i^2 = g_i g_i$ is central in G for each $i, 1 \leq i \leq k$. The dihedral group D_8 of order 8 and the quaternion group Q_8 are examples of such G .

Note that every finite group of nilpotency class two is obtained by taking direct products of finite groups of prime power order and class two. Therefore, G must be a 2-group direct product with abelian factors.

Let $\mathcal{C}(G)$ be the Cayley machine of G , then $\mathcal{G}(\mathcal{C}(G))$ is generated by

$$\{\mathcal{C}(G)_{g_1}, \mathcal{C}(G)_{g_2}, \dots, \mathcal{C}(G)_{g_k}\}.$$

Let $x = \mathcal{C}(G)_{g_1}^{-1}$. Then by (2.5), in wreath product coordinates,

$$x = 1 \left(\mathcal{C}(G)_{g_1}^{-1}, \mathcal{C}(G)_{g_2}^{-1}, \dots, \mathcal{C}(G)_{g_k}^{-1} \right).$$

It has infinite order. Identifying G with a subgroup of $\mathcal{C}(G)$ via $g \mapsto x\mathcal{C}(G)_g$, then we have

$$(2.6) \quad \mathcal{C}(G)_g = x^{-1}g, \quad \mathcal{C}(G)_g^{-1} = g^{-1}x.$$

Therefore, for any $g, h \in G$,

$$(2.7) \quad \mathcal{C}(G)_g^{-1}\mathcal{C}(G)_h = g^{-1}xx^{-1}h = g^{-1}h.$$

From previous subsection, $x^n g x^{-n}$ has depth $n + 1$ for $n \geq 0$. Also, we have

$$\begin{aligned} x^n g x^{-n} &= \mathcal{C}(G)_{g_1}^{-n} g \mathcal{C}(G)_{g_1}^n \\ &= (\mathcal{C}(G)_{g_1}^{-n}, \dots, \mathcal{C}(G)_{g_k}^{-n}) g (1, \dots, 1) (\mathcal{C}(G)_{g_1}^n, \dots, \mathcal{C}(G)_{g_k}^n) \\ &= (\mathcal{C}(G)_{g_1}^{-n}, \dots, \mathcal{C}(G)_{g_k}^{-n}) g (\mathcal{C}(G)_{g_1}^n, \dots, \mathcal{C}(G)_{g_k}^n) \\ &= g \left(\mathcal{C}(G)_{gg_1}^{-n} \mathcal{C}(G)_{g_1}^n, \mathcal{C}(G)_{gg_2}^{-n} \mathcal{C}(G)_{g_2}^n, \dots, \mathcal{C}(G)_{gg_k}^{-n} \mathcal{C}(G)_{g_k}^n \right) \\ &= g \left(\mathcal{C}_{gg_1}^{-n} \mathcal{C}_{g_1}^n, \mathcal{C}_{gg_2}^{-n} \mathcal{C}_{g_2}^n, \dots, \mathcal{C}_{gg_k}^{-n} \mathcal{C}_{g_k}^n \right), \end{aligned}$$

where in the last step, we write \mathcal{C} as $\mathcal{C}(G)$ for simplicity. We will keep on using this notation.

Let $N = \langle x^n g x^{-n} \mid n \in \mathbb{Z}, g \in G \rangle$, then $\mathcal{G}(\mathcal{C}(G)) = N \rtimes \langle x \rangle$, where x acts on N by conjugates. We show the following key lemma.

Lemma 2.2. *For any $n \geq 0$, any $f, g, h \in G$,*

$$\begin{aligned} x^n g x^{-n} h &= h x^{\lfloor \frac{n}{2} \rfloor} [h, g^{-1}] x^{-\lfloor \frac{n}{2} \rfloor} x^n g x^{-n}, \\ h x^n g x^{-n} &= x^n g x^{-n} x^{\lfloor \frac{n}{2} \rfloor} [g, h^{-1}] x^{-\lfloor \frac{n}{2} \rfloor} h, \end{aligned}$$

and $x^l [g, h] x^{-l}$ commutes with $x^m f x^{-m}$ as long as $n \geq l, m \geq 0$, where $\lfloor \frac{n}{2} \rfloor$ denotes the least integer greater than or equal to $\frac{n}{2}$.

Proof. The proof is by induction.

The case of $n = 0$ is trivial: $gh = h[h, g^{-1}]g$.

Let $n = 1$. Then

$$\begin{aligned} x g x^{-1} h &= g \left(\mathcal{C}_{gg_1}^{-1} \mathcal{C}_{g_1}, \mathcal{C}_{gg_2}^{-1} \mathcal{C}_{g_2}, \dots, \mathcal{C}_{gg_k}^{-1} \mathcal{C}_{g_k} \right) h (1, \dots, 1) \\ &= gh \left(\mathcal{C}_{ghg_1}^{-1} \mathcal{C}_{hg_1}, \mathcal{C}_{ghg_2}^{-1} \mathcal{C}_{hg_2}, \dots, \mathcal{C}_{ghg_k}^{-1} \mathcal{C}_{hg_k} \right), \end{aligned}$$

and

$$\begin{aligned} h x [h, g^{-1}] x^{-1} x g x^{-1} &= h x h^{-1} g h x^{-1} \\ &= h (1, \dots, 1) h^{-1} g h \left(\mathcal{C}_{h^{-1}ghg_1}^{-1} \mathcal{C}_{g_1}, \mathcal{C}_{h^{-1}ghg_2}^{-1} \mathcal{C}_{g_2}, \dots, \mathcal{C}_{h^{-1}ghg_k}^{-1} \mathcal{C}_{g_k} \right) \\ &= gh \left(\mathcal{C}_{h^{-1}ghg_1}^{-1} \mathcal{C}_{g_1}, \mathcal{C}_{h^{-1}ghg_2}^{-1} \mathcal{C}_{g_2}, \dots, \mathcal{C}_{h^{-1}ghg_k}^{-1} \mathcal{C}_{g_k} \right). \end{aligned}$$

Applying (2.6) and (2.7) we then have, for any $f \in G$,

$$\mathcal{C}_{ghf}^{-1} \mathcal{C}_{hf} = f^{-1} h^{-1} g^{-1} h f = \mathcal{C}_{h^{-1}ghf}^{-1} \mathcal{C}_f.$$

By comparing wreath product coordinates, $x g x^{-1} h = h x [h, g^{-1}] x^{-1} x g x^{-1}$. Similarly we have $h x g x^{-1} = x g x^{-1} x [g, h^{-1}] x^{-1} h$.

Since G is of nilpotency class two, both $[g, h]$ and $x[g, h]x^{-1}$ commute with f and $x f x^{-1}$, for any $g, h, f \in G$.

Let $n = 2$. Then we compute

$$\begin{aligned} x^2gx^{-2}h &= g\left(\mathcal{C}_{gg_1}^{-2}\mathcal{C}_{g_1}^2, \mathcal{C}_{gg_2}^{-2}\mathcal{C}_{g_2}^2, \dots, \mathcal{C}_{gg_k}^{-2}\mathcal{C}_{g_k}^2\right)h(1, \dots, 1) \\ &= gh\left(\mathcal{C}_{ghg_1}^{-2}\mathcal{C}_{hg_1}^2, \mathcal{C}_{ghg_2}^{-2}\mathcal{C}_{hg_2}^2, \dots, \mathcal{C}_{ghg_k}^{-2}\mathcal{C}_{hg_k}^2\right), \end{aligned}$$

and

$$\begin{aligned} hx[h, g^{-1}]x^{-1}x^2gx^{-2} &= h(1, \dots, 1)[h, g^{-1}]\left(\mathcal{C}_{h^{-1}ghg^{-1}g_1}^{-1}\mathcal{C}_{g_1}, \mathcal{C}_{h^{-1}ghg^{-1}g_2}^{-1}\mathcal{C}_{g_2}, \dots, \mathcal{C}_{h^{-1}ghg^{-1}g_k}^{-1}\mathcal{C}_{g_k}\right) \\ &\quad \cdot g\left(\mathcal{C}_{gg_1}^{-2}\mathcal{C}_{g_1}^2, \mathcal{C}_{gg_2}^{-2}\mathcal{C}_{g_2}^2, \dots, \mathcal{C}_{gg_k}^{-2}\mathcal{C}_{g_k}^2\right) \\ &= ghg^{-1}\left(\mathcal{C}_{h^{-1}ghg^{-1}g_1}^{-1}\mathcal{C}_{g_1}, \mathcal{C}_{h^{-1}ghg^{-1}g_2}^{-1}\mathcal{C}_{g_2}, \dots, \mathcal{C}_{h^{-1}ghg^{-1}g_k}^{-1}\mathcal{C}_{g_k}\right) \\ &\quad \cdot g\left(\mathcal{C}_{gg_1}^{-2}\mathcal{C}_{g_1}^2, \mathcal{C}_{gg_2}^{-2}\mathcal{C}_{g_2}^2, \dots, \mathcal{C}_{gg_k}^{-2}\mathcal{C}_{g_k}^2\right) \\ &= gh\left(\mathcal{C}_{h^{-1}ghg_1}^{-1}\mathcal{C}_{gg_1}\mathcal{C}_{gg_1}^{-2}\mathcal{C}_{g_1}^2, \mathcal{C}_{h^{-1}ghg_2}^{-1}\mathcal{C}_{gg_2}\mathcal{C}_{gg_2}^{-2}\mathcal{C}_{g_2}^2, \dots, \mathcal{C}_{h^{-1}ghg_k}^{-1}\mathcal{C}_{gg_k}\mathcal{C}_{gg_k}^{-2}\mathcal{C}_{g_k}^2\right). \end{aligned}$$

For any $f \in G$, applying (2.7) we compute

$$\begin{aligned} \mathcal{C}_{ghf}^{-2}\mathcal{C}_{hf}^2 &= \mathcal{C}_{ghf}^{-1}f^{-1}h^{-1}g^{-1}hf\mathcal{C}_{hf} \\ &= f^{-1}h^{-1}g^{-1}(xf^{-1}h^{-1}g^{-1}hfx^{-1}hf) \\ &= f^{-1}h^{-1}g^{-1}hfxg^{-1}x^{-1}, \end{aligned}$$

and

$$\begin{aligned} \mathcal{C}_{h^{-1}ghf}^{-1}\mathcal{C}_{gf}\mathcal{C}_{gf}^{-2}\mathcal{C}_f^2 &= ((h^{-1}ghf)^{-1}gf)(f^{-1}g^{-1}fxg^{-1}x^{-1}) \\ &= f^{-1}h^{-1}g^{-1}hfxg^{-1}x^{-1} = \mathcal{C}_{ghf}^{-2}\mathcal{C}_{hf}^2. \end{aligned}$$

So, $x^2gx^{-2}h = hx[h, g^{-1}]x^{-1}x^2gx^{-2}$, since they have same wreath product coordinates.

On the other hand, notice that

$$[h, g^{-1}][g, h^{-1}] = h^{-1}ghg^{-1}g^{-1}hgh^{-1} = h^{-1}gg^{-1}hgh^{-1}hg^{-1} = 1,$$

then we have

$$\begin{aligned} hx^2gx^{-2} &= hx^2gx^{-2}x[h, g^{-1}]x^{-1}x[g, h^{-1}]x^{-1} \\ &= hxxgx^{-1}[h, g^{-1}]x^{-1}x[g, h^{-1}]x^{-1} \\ &= hx[h, g^{-1}]xgx^{-1}x^{-1}x[g, h^{-1}]x^{-1} \\ &= hx[h, g^{-1}]x^{-1}x^2gx^{-2}x[g, h^{-1}]x^{-1} \\ &= x^2gx^{-2}hx[g, h^{-1}]x^{-1} = x^2gx^{-2}x[g, h^{-1}]x^{-1}h. \end{aligned}$$

Since G is of nilpotency class two, then $x^2[g, h]x^{-2}$ commutes with f and x^2fx^{-2} , for any $g, h, f \in G$. Also we have

$$\begin{aligned} x^2[g, h]x^{-2}xfx^{-1} &= xx[g, h]x^{-1}fx^{-1} \\ &= xfx[g, h]x^{-1}x^{-1} \\ &= xfx^{-1}x^2[g, h]x^{-2}. \end{aligned}$$

Similarly, $[g, h]$ and $x[g, h]x^{-1}$ commute with f, xfx^{-1} and x^2fx^{-2} , for any $g, h, f \in G$. Then we proved the lemma for the case of $n = 2$.

Now we assume the lemma is true for all $m \leq 2n$, we need to show the cases of $2n + 1$ and $2n + 2$.

Applying (2.7), we have

$$\begin{aligned} &x^{2n+1}gx^{-2n-1}h \\ &= g\left(\mathcal{C}_{gg_1}^{-2n-1}\mathcal{C}_{g_1}^{2n+1}, \mathcal{C}_{gg_2}^{-2n-1}\mathcal{C}_{g_2}^{2n+1}, \dots, \mathcal{C}_{gg_k}^{-2n-1}\mathcal{C}_{g_k}^{2n+1}\right)h(1, \dots, 1) \\ &= gh\left(\mathcal{C}_{ghg_1}^{-2n-1}\mathcal{C}_{hg_1}^{2n+1}, \mathcal{C}_{ghg_2}^{-2n-1}\mathcal{C}_{hg_2}^{2n+1}, \dots, \mathcal{C}_{ghg_k}^{-2n-1}\mathcal{C}_{hg_k}^{2n+1}\right), \end{aligned}$$

and similarly $x^{2n}gx^{-2n}h = gh\left(\mathcal{C}_{ghg_1}^{-2n}\mathcal{C}_{hg_1}^{2n}, \mathcal{C}_{ghg_2}^{-2n}\mathcal{C}_{hg_2}^{2n}, \dots, \mathcal{C}_{ghg_k}^{-2n}\mathcal{C}_{hg_k}^{2n}\right)$.

On the other hand, we compute

$$\begin{aligned} &hx^{n+1}[h, g^{-1}]x^{-n-1}x^{2n+1}gx^{-2n-1} \\ &= h[h, g^{-1}]\left(\mathcal{C}_{[h, g^{-1}]g_1}^{-n-1}\mathcal{C}_{g_1}^{n+1}, \mathcal{C}_{[h, g^{-1}]g_2}^{-n-1}\mathcal{C}_{g_2}^{n+1}, \dots, \mathcal{C}_{[h, g^{-1}]g_k}^{-n-1}\mathcal{C}_{g_k}^{n+1}\right) \\ &\quad g\left(\mathcal{C}_{gg_1}^{-2n-1}\mathcal{C}_{g_1}^{2n+1}, \mathcal{C}_{gg_2}^{-2n-1}\mathcal{C}_{g_2}^{2n+1}, \dots, \mathcal{C}_{gg_k}^{-2n-1}\mathcal{C}_{g_k}^{2n+1}\right) \\ &= gh\left(\mathcal{C}_{[h, g^{-1}]gg_1}^{-n-1}\mathcal{C}_{gg_1}^{n+1}\mathcal{C}_{g_1}^{-2n-1}\mathcal{C}_{g_1}^{2n+1}, \mathcal{C}_{[h, g^{-1}]gg_2}^{-n-1}\mathcal{C}_{gg_2}^{n+1}\mathcal{C}_{g_2}^{-2n-1}\mathcal{C}_{g_2}^{2n+1}, \right. \\ &\quad \left. \dots, \mathcal{C}_{[h, g^{-1}]gg_k}^{-n-1}\mathcal{C}_{gg_k}^{n+1}\mathcal{C}_{g_k}^{-2n-1}\mathcal{C}_{g_k}^{2n+1}\right) \\ &= gh\left(\mathcal{C}_{[h, g^{-1}]gg_1}^{-n-1}\mathcal{C}_{gg_1}^{-n}\mathcal{C}_{g_1}^{2n+1}, \mathcal{C}_{[h, g^{-1}]gg_2}^{-n-1}\mathcal{C}_{gg_2}^{-n}\mathcal{C}_{g_2}^{2n+1}, \dots, \mathcal{C}_{[h, g^{-1}]gg_k}^{-n-1}\mathcal{C}_{gg_k}^{-n}\mathcal{C}_{g_k}^{2n+1}\right), \end{aligned}$$

and similarly

$$\begin{aligned} &hx^n[h, g^{-1}]x^{-n}x^{2n}gx^{-2n} \\ &= gh\left(\mathcal{C}_{[h, g^{-1}]gg_1}^{-n}\mathcal{C}_{gg_1}^{-n}\mathcal{C}_{g_1}^{2n}, \mathcal{C}_{[h, g^{-1}]gg_2}^{-n}\mathcal{C}_{gg_2}^{-n}\mathcal{C}_{g_2}^{2n}, \dots, \mathcal{C}_{[h, g^{-1}]gg_k}^{-n}\mathcal{C}_{gg_k}^{-n}\mathcal{C}_{g_k}^{2n}\right). \end{aligned}$$

Note that, by inductive hypothesis and comparing wreath product coordinates, we have, for any $f \in G$,

$$\mathcal{C}_{ghf}^{-2n}\mathcal{C}_{hf}^{2n} = \mathcal{C}_{[h, g^{-1]}gf}^{-n}\mathcal{C}_{gf}^{-n}\mathcal{C}_f^{2n}.$$

Then, applying (2.6) and (2.7), for any $f \in G$, we compute

$$\begin{aligned} &\mathcal{C}_{ghf}^{-2n-1}\mathcal{C}_{hf}^{2n+1} \\ &= \mathcal{C}_{ghf}^{-1}\mathcal{C}_{[h, g^{-1]}gf}^{-n}\mathcal{C}_{gf}^{-n}\mathcal{C}_f^{2n}\mathcal{C}_{hf} \\ &= (ghf)^{-1}x\left(\left([h, g^{-1]}gf\right)^{-1}x\right)^n\left((gf)^{-1}x\right)^{n-1} \\ &\quad \cdot f^{-1}g^{-1}f(x^{-1}f)^{2n-1}x^{-1}hf \end{aligned}$$

$$\begin{aligned}
&= (ghf)^{-1} \left(\prod_{l=1}^n x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) \left(\prod_{l=n+1}^{2n-1} x^l (gf)^{-1} x^{-l} \right) \\
&\quad \cdot x^{2n} f^{-1} g^{-1} f x^{-2n} \left(\prod_{l=1}^{2n-1} x^l f x^{-l} \right) hf \\
&= (ghf)^{-1} h \left(\prod_{l=1}^n x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) \left(\prod_{l=n+1}^{2n-1} x^l (gf)^{-1} x^{-l} \right) \\
&\quad \cdot x^{2n} f^{-1} g^{-1} f x^{-2n} \left(\prod_{l=1}^{2n-1} x^l f x^{-l} \right) f \left(\prod_{l=1}^{n-1} x^l [gf, h]^2 x^{-l} \right) \\
&\quad \cdot x^n [gf, h] [f^{-1} g^{-1} f, h] [f, h] x^{-n} \left(\prod_{l=1}^{n-1} x^l [f, h]^2 x^{-l} \right) \\
&= (ghf)^{-1} h \left(\prod_{l=1}^n x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) \left(\prod_{l=n+1}^{2n-1} x^l (gf)^{-1} x^{-l} \right) \\
&\quad \cdot x^{2n} f^{-1} g^{-1} f x^{-2n} \left(\prod_{l=1}^{2n-1} x^l f x^{-l} \right) f \\
&= ([h, g^{-1}]gf)^{-1} x (([h, g^{-1}]gf)^{-1} x)^n ((gf)^{-1} x)^{n-1} \\
&\quad \cdot f^{-1} g^{-1} f (x^{-1} f)^{2n-1} x^{-1} f,
\end{aligned}$$

where $[gf, h][f^{-1}g^{-1}f, h][f, h] = 1$ follows from direct calculation. Also we have

$$\begin{aligned}
&\mathcal{C}_{[h, g^{-1}]gf}^{-n-1} \mathcal{C}_{gf}^{-n} \mathcal{C}_f^{2n+1} \\
&= (([h, g^{-1}]gf)^{-1} x)^{n+1} ((gf)^{-1} x)^{n-1} f^{-1} g^{-1} f (x^{-1} f)^{2n} \\
&= ([h, g^{-1}]gf)^{-1} x (([h, g^{-1}]gf)^{-1} x)^n ((gf)^{-1} x)^{n-1} f^{-1} g^{-1} f (x^{-1} f)^{2n-1} x^{-1} f.
\end{aligned}$$

Thus we get

$$(2.8) \quad \mathcal{C}_{ghf}^{-2n-1} \mathcal{C}_{hf}^{2n+1} = \mathcal{C}_{[h, g^{-1}]gf}^{-n-1} \mathcal{C}_{gf}^{-n} \mathcal{C}_f^{2n+1}.$$

So, by comparing wreath product coordinates, we obtain

$$x^{2n+1} g x^{-2n-1} h = h x^{n+1} [h, g^{-1}] x^{-n-1} x^{2n+1} g x^{-2n-1}.$$

On the other hand, by commutativity we have

$$\begin{aligned}
h x^{2n+1} g x^{-2n-1} &= h x^{2n+1} g x^{-2n-1} x^{n+1} [h, g^{-1}] x^{-n-1} x^{n+1} [g, h^{-1}] x^{-n-1} \\
&= h x^{n+1} [h, g^{-1}] x^n g x^{-n} x^{-n-1} x^{n+1} [g, h^{-1}] x^{-n-1} \\
&= x^{2n+1} g x^{-2n-1} h x^{n+1} [g, h^{-1}] x^{-n-1} \\
&= x^{2n+1} g x^{-2n-1} x^{n+1} [g, h^{-1}] x^{-n-1} h.
\end{aligned}$$

For any $f, g, h \in G$, $0 \leq m \leq 2n + 1$, the commutativity of $x^m f x^{-m}$ with $x^{2n+1}[g, h]x^{-2n-1}$ and of $x^m[g, h]x^m$ with $x^{2n+1}f x^{-2n-1}$ follow from the same trick. So we proved the case of $2n + 1$.

Now we prove the case of $2n + 2$. By previous calculation, we have

$$x^{2n+2}g x^{-2n-2}h = gh \left(C_{ghg_1}^{-2n-2} C_{hg_1}^{2n+2}, C_{ghg_2}^{-2n-2} C_{hg_2}^{2n+2}, \dots, C_{ghg_k}^{-2n-2} C_{hg_k}^{2n+2} \right),$$

and

$$\begin{aligned} &hx^{n+1}[h, g^{-1}]x^{-n-1}x^{2n+2}gx^{-2n-2} \\ &= gh \left(C_{[h, g^{-1}]gg_1}^{-n-1} C_{gg_1}^{-n-1} C_{g_1}^{2n+2}, C_{[h, g^{-1}]gg_2}^{-n-1} C_{gg_2}^{-n-1} C_{g_2}^{2n+2}, \right. \\ &\quad \left. \dots, C_{[h, g^{-1}]gg_k}^{-n-1} C_{gg_k}^{-n-1} C_{g_k}^{2n+2} \right). \end{aligned}$$

Again we compare wreath product coordinates. Applying (2.8) and (2.7), for any $f \in G$,

$$\begin{aligned} C_{ghf}^{-2n-2} C_{hf}^{2n+2} &= C_{ghf}^{-1} C_{ghf}^{-2n-1} C_{hf}^{2n+1} C_{hf} = C_{ghf}^{-1} C_{[h, g^{-1}]gf}^{-n-1} C_{gf}^{-n} C_f^{2n+1} C_{hf} \\ &= (ghf)^{-1} x \left(([h, g^{-1}]gf)^{-1} x \right)^{n+1} \left((gf)^{-1} x \right)^{n-1} f^{-1} g^{-1} f (x^{-1} f)^{2n} x^{-1} h f \\ &= (ghf)^{-1} \left(\prod_{l=1}^{n+1} x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) \left(\prod_{l=n+2}^{2n} x^l (gf)^{-1} x^{-l} \right) x^{2n+1} f^{-1} g^{-1} f \\ &\quad \cdot x^{-2n-1} \left(\prod_{l=1}^{2n} x^l f x^{-l} \right) h f \\ &= (ghf)^{-1} h \left(\prod_{l=1}^{n+1} x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) \left(\prod_{l=n+2}^{2n} x^l (gf)^{-1} x^{-l} \right) x^{2n+1} f^{-1} g^{-1} f \\ &\quad \cdot x^{-2n-1} \left(\prod_{l=1}^{2n} x^l f x^{-l} \right) f \left(\prod_{l=1}^n (x^l [gf, h][gf, h] x^{-l}) \right) x^{n+1} [f^{-1} g^{-1} f, h] x^{-n-1} \\ &\quad \cdot \left(\prod_{l=1}^n (x^l [f, h][f, h] x^{-l}) \right) \\ &= (ghf)^{-1} h \left(\prod_{l=1}^n x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) x^{n+1} ([h, g^{-1}]gf)^{-1} [f^{-1} g^{-1} f, h] x^{-n-1} \\ &\quad \cdot \left(\prod_{l=n+2}^{2n} x^l (gf)^{-1} x^{-l} \right) x^{2n+1} f^{-1} g^{-1} f x^{-2n-1} \left(\prod_{l=1}^{2n} x^l f x^{-l} \right) f. \end{aligned}$$

On the other hand,

$$\begin{aligned} &C_{[h, g^{-1}]gf}^{-n-1} C_{gf}^{-n-1} C_f^{2n+2} \\ &= \left(([h, g^{-1}]gf)^{-1} x \right)^{n+1} \left((gf)^{-1} x \right)^n f^{-1} g^{-1} f (x^{-1} f)^{2n+1} \end{aligned}$$

$$\begin{aligned}
&= (ghf)^{-1}h \left(\prod_{l=1}^n x^l ([h, g^{-1}]gf)^{-1} x^{-l} \right) \left(\prod_{l=n+1}^{2n} x^l (gf)^{-1} x^{-l} \right) x^{2n+1} f^{-1} g^{-1} f \\
&\quad \cdot x^{-2n-1} \left(\prod_{l=1}^{2n} x^l f x^{-l} \right) f.
\end{aligned}$$

Since $([h, g^{-1}]gf)^{-1}[f^{-1}g^{-1}f, h] = (gf)^{-1}$, then

$$C_{ghf}^{-2n-2} C_{hf}^{2n+2} = C_{[h, g^{-1}]gf}^{-n-1} C_{gf}^{-n-1} C_f^{2n+2},$$

and thus

$$x^{2n+2} g x^{-2n-2} h = h x^{n+1} [h, g^{-1}] x^{-n-1} x^{2n+2} g x^{-2n-2}.$$

Moreover, this implies

$$h x^{2n+2} g x^{-2n-2} = x^{2n+2} g x^{-2n-2} x^{n+1} [g, h^{-1}] x^{-n-1} h,$$

by the commutativity trick.

For any $f, g, h \in G$, $0 \leq m \leq 2n + 2$, the commutativity of $x^m f x^{-m}$ with $x^{2n+2} [g, h] x^{-2n-2}$ and of $x^m [g, h] x^m$ with $x^{2n+2} f x^{-2n-2}$ follow from nilpotency. So we prove the case of $2n + 2$ and hence the lemma. \square

Lemma 2.3. *For any $g, h \in G, n, m \in \mathbb{Z}$, $x^n [g, h] x^{-n}$ lies in the center of N , and*

$$x^n g x^{-n} x^m h x^{-m} = x^m h x^{-m} x^{\lfloor \frac{n+m}{2} \rfloor} [h, g^{-1}] x^{-\lfloor \frac{n+m}{2} \rfloor} x^n g x^{-n}.$$

Proof. We assume $n \geq m$.

Let $f \in G$. We compute

$$\begin{aligned}
x^n [g, h] x^{-n} x^m f x^{-m} &= x^m x^{n-m} [g, h] x^{m-n} f x^{-m} \\
&= x^m f x^{n-m} [g, h] x^{m-n} x^{-m} \\
&= x^m f x^{-m} x^n [g, h] x^{-n},
\end{aligned}$$

and

$$\begin{aligned}
x^n g x^{-n} x^m h x^{-m} &= x^m x^{n-m} g x^{m-n} h x^{-m} \\
&= x^m h x^{\lfloor \frac{n-m}{2} \rfloor} [h, g^{-1}] x^{-\lfloor \frac{n-m}{2} \rfloor} x^{n-m} g x^{m-n} x^{-m} \\
&= x^m h x^{-m} x^{\lfloor \frac{n+m}{2} \rfloor} [h, g^{-1}] x^{-\lfloor \frac{n+m}{2} \rfloor} x^n g x^{-n} \\
&= x^m h x^{-m} x^{\lfloor \frac{n+m}{2} \rfloor} [h, g^{-1}] x^{-\lfloor \frac{n+m}{2} \rfloor} x^n g x^{-n}.
\end{aligned}$$

The case of $n \leq m$ is similar. \square

Lemma 2.4. *Given any nontrivial torsion element $\gamma \in \mathcal{G}(\mathcal{C}(G))$, it can be written uniquely in the following form:*

$$(2.9) \quad \gamma = x^{i_1} f_1 x^{-i_1} x^{i_2} f_2 x^{-i_2} \dots x^{i_j} f_j x^{-i_j},$$

where $i_1 < i_2 < \dots < i_j$ are integers, $j \geq 1$ and $f_1, f_2, \dots, f_j \in G \setminus \{g_1 = 1\}$.

Proof. Since γ is a product of conjugates by x of elements in G , by Lemma 2.3, γ can be written in the form of (2.9). So we only need to show the uniqueness.

Let $\gamma = x^{i_1} f_1 x^{-i_1} x^{i_2} f_2 x^{-i_2} \dots x^{i_j} f_j x^{-i_j} = 1$, where $i_1 < i_2 < \dots < i_j$ and $f_1, f_2, \dots, f_j \in G$. Then $1 = x^{-i_1} \gamma x^{i_1} = f_1 x^{i_2 - i_1} f_2 x^{-i_2 + i_1} \dots x^{i_j - i_1} f_j x^{-i_j + i_1}$ has depth $i_j - i_1 + 1 \geq 1$, if $f_j \neq 1$. Hence, by an inductive argument, we have $f_i = 1, 1 \leq i \leq j$. It completes the proof. \square

Proof of Theorem 1.1 . Note that [17] $\mathcal{G}(\mathcal{C}(G)) = N \rtimes \langle x \rangle$ and the identities in Lemma 2.3 is equivalent to the relations in Theorem 1.1. Then the theorem follows from Lemma 2.3 and Lemma 2.4. \square

In the end of [13], Kambites, Silva and Steinberg conjectured that the automata group associated to any finite nonabelian group can not have bounded torsion. The following corollary disproves the conjecture.

Corollary 2.5. *Let G be a finite nilpotent group of class 2. Assume the square of each element of G is central, then $\mathcal{G}(\mathcal{C}(G))$ has bounded torsion.*

Proof. Let $|G| = k$. Note that k is even. Let γ be a torsion element. Since every commutator has order at most 2, then by Lemma 2.4 and Theorem 1.1 we have $\gamma^{2k} = 1$, i.e., the order of any torsion element is a factor of $2k$. \square

2.3. Nonembedding into wreath products.

Lemma 2.6. *Let G be a finite 2-group of nilpotency class 2. Then G has a subgroup H in which each square element is central in H .*

Proof. By assumption on G , there exists a noncentral element $g \in G$ such that g^2 is central. Similarly, there exists $h \in G$ so that it does not commute with g but h^2 commutes with g . Then the subgroup H of G generated by g and h is nilpotent of class 2. We show each square element in H is central in H . Since g^2 and h^2 are central, it suffices to show for squares of alternate products of g or g^{-1} with h or h^{-1} . Since $g^{-1} = gg^{-1}g^{-1}$ and $h^{-1} = hh^{-1}h^{-1}$, it reduces to squares of alternate products of g with h . Since $(ghg)^2 = ghgghg = g^4h^2$, by symmetry we only need to show that $(gh)^2$ is central. Indeed, we have $ghghh(ghgh)^{-1} = ghghhh^{-1}g^{-1}h^{-1}g^{-1}h^{-1} = gh(ghg^{-1}h^{-1})g^{-1}h^{-1} = ghg^{-1}ghg^{-1}h^{-1}h^{-1} = ghhg^{-1}h^{-1}h^{-1} = 1$, and similarly $ghghg(gghgh)^{-1} = 1$ by symmetry. \square

Proof of Theorem 1.2. Let G' be the 2-group. Let g be a noncentral element in G' such that g^2 is central. Let $h \in G'$ so that it does not commute with g but h^2 commutes with g . Then the subgroup H of G generated by g and h is nilpotent of class 2. By previous lemma, each square element of H is central in H .

For each $n \in \mathbb{N}$, we consider the element

$$\gamma_n = (x^n h x^{-n}) g (x^n h^{-1} x^{-n}).$$

Each such element is a conjugate of the torsion element g by another torsion element $x^n h x^{-n}$. γ_n has depth at most $n + 1$. Since every conjugacy class in the torsion subgroup of any wreath product of a finite group with a torsion-free group is finite, see [13] Lemma 6.4, it suffices to show that γ_n has depth at least $\lfloor \frac{n}{2} \rfloor$. Indeed, $\gamma_n = g x^{\lfloor \frac{n}{2} \rfloor} [g, h^{-1}] x^{-\lfloor \frac{n}{2} \rfloor}$ has depth $\lfloor \frac{n}{2} \rfloor + 1$ by Lemma 2.1. \square

Proof of Theorem 1.3. Combining Theorem 1.2 with results in the appendix of [13], the theorem follows. \square

3. Cross-wired lamplighter groups

The Cayley graph of lamplighter groups can be examples of Diestel–Leader graphs, for particular choices of generators [3, 14, 22, 23]. *Cross-wired lamplighter groups* [2] are defined to be cocompact lattices of the isometry group of Diestel–Leader graphs. Cornulier, Fisher and Kashyap [2] give a necessary and sufficient condition for a locally compact group to be isomorphic to a closed cocompact subgroup in the isometry group of a Diestel–Leader graph. The following is the sufficient condition for the case of discrete groups.

Theorem 3.1. [2] *Let Γ be a discrete group, with a semidirect product decomposition $\Gamma = H \rtimes \langle t \rangle$, where H is infinite and t is torsion free. Assume that H has subgroups L and L' such that:*

- tLt^{-1} and $t^{-1}L't$ are finite index subgroups, of index m and n , in L and L' respectively;
- $\bigcup_{k \in \mathbb{Z}} t^{-k} L t^k = \bigcup_{k \in \mathbb{Z}} t^k L' t^{-k} = H$ (these are increasing unions);
- $L \cap L'$ is finite;
- the double coset space $L \backslash H / L'$ is finite.

Then Γ is finitely generated, $m = n$ and Γ has a proper, transitive action on some Diestel–Leader graph.

3.1. Proof of Theorem 1.4.

Proof of Theorem 1.4. In order to show the automata groups are cross-wired lamplighters, it suffices to check the conditions in above theorem.

Let

$$\begin{aligned} G &= \{g_1 = 1, g_2, \dots, g_k\}, \\ L &= \langle x^n G x^{-n}, n \geq 0 \rangle, \\ L' &= \langle x^n G x^{-n}, n \leq -1 \rangle. \end{aligned}$$

- (1) We show that xLx^{-1} and $x^{-1}L'x$ are finite index subgroups in L and L' respectively. Note that $xLx^{-1} = \langle x^n G x^{-n}, n \geq 1 \rangle < L$. Lemma 2.2 implies that every element in L can be written as an element in $g(xLx^{-1})$ for some $g \in G$. So the index of xLx^{-1} in L is finite. Similarly $x^{-1}L'x = \langle x^n G x^{-n}, n \leq -1 \rangle$ has finite index in L' .

- (2) We show that $\bigcup_{n \in \mathbb{Z}} x^{-n} L x^n = \bigcup_{n \in \mathbb{Z}} x^n L' x^{-n} = N$, and the unions are increasing. Note that $\bigcup_{n \in \mathbb{Z}} x^{-n} L x^n$ is a subgroup of N and $\bigcup_{n \in \mathbb{Z}} x^{-n} L x^n$ contains all the generators of N . Thus

$$\bigcup_{n \in \mathbb{Z}} x^{-n} L x^n = N.$$

Similarly we have $\bigcup_{n \in \mathbb{Z}} x^n L' x^{-n} = N$. The unions are the unions of increasing subgroups, by the definitions of L and L' .

- (3) We show $L \cap L'$ is finite. Indeed, it follows from Lemma 2.4 that $L \cap L'$ is trivial. We give an alternative proof below using the idea of depth. By Lemma 2.1, each generator of L has finite depth, so do the elements of L . It suffices to show every nontrivial element of L' has infinite depth. Let $1 \neq g \in G$. Since

$$\begin{aligned} x^{-1} g x &= (C_{g_1}, C_{g_2}, \dots, C_{g_k}) g (C_{g_1}^{-1}, C_{g_2}^{-1}, \dots, C_{g_k}^{-1}) \\ &= g (C_{g g_1} C_{g_1}^{-1}, C_{g g_2} C_{g_2}^{-1}, \dots, C_{g g_k} C_{g_k}^{-1}) \\ &= g (x^{-1} g g_1 (g_1)^{-1} x, x^{-1} g g_2 (g_2)^{-1} x, \dots, x^{-1} g g_k (g_k)^{-1} x) \\ &= g (x^{-1} g x, x^{-1} g x, \dots, x^{-1} g x), \end{aligned}$$

then $x^{-1} g x$ acts on any infinite word in G^ω by multiplying g on the left to each letter in the word, and hence has infinite depth. Assume $x^n g x^{-n}$ has finite depth m for some $n \leq -2$. Then by Lemma 2.1, $x^{-1} g x$ has depth at most $m - n - 1$, which is a contradiction. Thus $x^n g x^{-n}$ has infinite depth for each $n \leq -1$.

Let

$$1 \neq \gamma = x^{n_1} f_1 x^{-n_1} x^{n_2} f_2 x^{-n_2} \dots x^{n_p} f_p x^{-n_p}$$

be a reduced element of L' , where $p \in \mathbb{N}, n_1, n_2, \dots, n_p \leq -1$. Then by Lemma 2.4, we can rewrite this element as

$$x^{m_1} h_1 x^{-m_1} x^{m_2} h_2 x^{-m_2} \dots x^{m_q} h_q x^{-m_q},$$

for some $q \in \mathbb{N}, m_1 < m_2 < \dots < m_q \leq -1$. Then

$$\begin{aligned} x^{-m_1-1} (x^{m_1} h_1 x^{-m_1} x^{m_2} h_2 x^{-m_2} \dots x^{m_q} h_q x^{-m_q}) x^{m_1+1} \\ = x^{-1} h_1 x x^{m_2-m_1-1} h_2 x^{-m_2+m_1+1} \dots x^{m_q-m_1-1} h_q x^{-m_q+m_1+1}, \end{aligned}$$

has infinite depth, since all conjugates of $h_i, i \geq 2$ in the product have finite depth but $x^{-1} h_1 x$. Thus, by Lemma 2.1, γ has infinite depth. Therefore, $L \cap L'$ is trivial.

- (4) We show that the double coset space $L \backslash N / L'$ is finite. It follows from Lemma 2.3, as shown in the proof of (3) that products of conjugates can be written as products of conjugates in either increasing or decreasing order, that $L \backslash N / L'$ is trivial. \square

Remark 3.2. A cross-wired lamplighter is said to be *symmetric* [2] if it admits an automorphism α such that if π is the projection to \mathbb{Z} (which is unique up to sign) then $\pi \circ \alpha = -\pi$, and *virtually symmetric* if it admits a symmetric subgroup of finite index. $\mathcal{G}(\mathcal{C}(D_8))$ is symmetric, but $\mathcal{G}(\mathcal{C}(Q_8))$ is not symmetric.

Remark 3.3. The lamplighter group $F \wr \mathbb{Z}$ can be interpreted as follows. The generator of \mathbb{Z} describes the walk of a lamplighter along an infinite street with a streetlamp at each integer. Each streetlamp has $|F|$ states. The generators of F represent the ability of the lamplighter to change the state of the lamp at his current position. This description is most intuitive where $F = \mathbb{Z}_2$ and lamps are simply on or off. For the group G in Theorem 1.1, the cross-wired lamplighter $\mathcal{G}(\mathcal{C}(G)) = \langle G, x \rangle$ can be interpreted in a similar but more complicated way. The generator x still describe the walk of a lamplighter. Each streetlamp has $|G|$ states, including off as a state represented by $1 \in G$. The states of lamps are determined by the normal form in Lemma 2.4. The generators of G now represent the ability of the lamplighter to change the states of the lamps not only at his current position, but also at some positions between his and the [mid] position of his and the position of the lamp to the farthest right (positive direction) which is on. The change of state of lamps on the right is up to a commutator state. This interpretation gives one cross-wired pattern for cross-wired lamplighter groups.

4. Linearity of automata groups

In this chapter, we are going to prove Theorem 1.5. In particular, the automata groups in Theorem 1.5 are essentially those linear examples of cross-wired lamplighter groups constructed in [2]. We can only show linearity of the cases of Q_8 and M_{2^n} . It is interesting if one can show all cases considered in Theorem 1.1. We begin with some notations and lemmas.

4.1. Notations. Let $\text{UT}_m(\mathbb{Z}_2[t^{\pm 1}])$ be $m \times m$ upper unitriangular matrices over Laurent polynomial ring $\mathbb{Z}_2[t^{\pm 1}]$. Let $g = (g_{ij}), h = (h_{ij})$ be elements in $\text{UT}_m(\mathbb{Z}_2[t^{\pm 1}])$ and $\bar{g} = (\bar{g}_{ij}), \bar{h} = (\bar{h}_{ij})$ be their inverses.

Lemma 4.1. $\bar{g}_{ii} = 1, \bar{g}_{i,i+1} = g_{i,i+1}$, and $\bar{g}_{ij}, j > i$, satisfies the recursive formula

$$\bar{g}_{ij} = \sum_{k=i+1}^j g_{ik} \bar{g}_{kj}.$$

Proof. $\bar{g}_{ii} = 1$. For $j > i$, we have

$$0 = \sum_{l=i}^j g_{il} \bar{g}_{lj} = g_{ii} \bar{g}_{ij} + \sum_{l=i+1}^j g_{il} \bar{g}_{lj} = \bar{g}_{ij} + \sum_{l=i+1}^j g_{il} \bar{g}_{lj}. \quad \square$$

The following lemma will be very helpful in calculation.

Lemma 4.2. *Suppose $[g, h]_{i,j} = 0$ as long as $0 < j - i < m - 1$, then*

$$[g, h]_{1m} = \sum_{k=2}^{m-1} (g_{1k}h_{km} + h_{1k}g_{km}).$$

Proof.

$$\begin{aligned} [g, h]_{1m} &= \sum_{i=1}^m \sum_{k=i}^m \sum_{j=k}^m \bar{g}_{1i} \bar{h}_{ik} g_{kj} h_{jm} \\ &= \sum_{k=1}^m \sum_{j=k}^m \bar{h}_{1k} g_{kj} h_{jm} + \sum_{i=2}^m \sum_{k=i}^m \sum_{j=k}^m \bar{g}_{1i} \bar{h}_{ik} g_{kj} h_{jm} \\ &= \sum_{j=1}^m g_{1j} h_{jm} + \sum_{k=2}^m \sum_{j=k}^m \sum_{l=2}^k h_{1l} \bar{h}_{lk} g_{kj} h_{jm} + \sum_{i=2}^m \sum_{k=i}^m \sum_{j=k}^m \sum_{l=2}^i g_{1l} \bar{g}_{li} \bar{h}_{ik} g_{kj} h_{jm} \\ &= \sum_{j=1}^m g_{1j} h_{jm} + \sum_{l=2}^m \sum_{k=l}^m \sum_{j=k}^m h_{1l} \bar{h}_{lk} g_{kj} h_{jm} + \sum_{l=2}^m \sum_{i=l}^m \sum_{k=i}^m \sum_{j=k}^m g_{1l} \bar{g}_{li} \bar{h}_{ik} g_{kj} h_{jm} \\ &= \sum_{j=1}^m g_{1j} h_{jm} + \sum_{l=2}^m h_{1l} \sum_{k=l}^m \sum_{j=k}^m \bar{h}_{lk} g_{kj} h_{jm} + \sum_{l=2}^m g_{1l} \sum_{i=l}^m \sum_{k=i}^m \sum_{j=k}^m \bar{g}_{li} \bar{h}_{ik} g_{kj} h_{jm} \\ &= \sum_{j=1}^m g_{1j} h_{jm} + \sum_{l=2}^m h_{1l} g_{lm} + \sum_{l=2}^{m-1} g_{1l} 0 + g_{1m} = \sum_{k=2}^{m-1} (g_{1k}h_{km} + h_{1k}g_{km}). \quad \square \end{aligned}$$

We recall here the commutator identities in group theory:

$$(4.1) \quad [a, bc] = [a, c]c^{-1}[a, b]c, \quad [ab, c] = b^{-1}[a, c]b[b, c],$$

where a, b, c are elements of a group F .

For the group G in Theorem 1.1, $\mathcal{G}(\mathcal{C}(G)) = \langle G, x \rangle$. Let

$$\mathcal{G}_2(\mathcal{C}(G)) := \langle G, xGx^{-1}, x^2 \rangle.$$

Then it is an index two subgroup of $\mathcal{G}(\mathcal{C}(G))$.

4.2. Linearity of $\mathcal{G}(\mathcal{C}(Q_8))$. Let

$$Q_8 = \langle a, b \mid a^4 = 1, a^2 = b^2, b^{-1}ab = a^{-1} \rangle.$$

It has center $Z(Q_8) = \langle a^2 \rangle$. Then $\mathcal{G}(\mathcal{C}(Q_8))$ is generated by $\{a, b, x\}$, and $\mathcal{G}_2(\mathcal{C}(Q_8))$ is generated by $\{a, b, xax^{-1}, xbx^{-1}, x^2\}$.

Lemma 4.3. *Any nontrivial torsion element of $\mathcal{G}(\mathcal{C}(Q_8))$ can be uniquely written in the following form:*

$$\left(\prod_{r=1}^k x^{i_r} a x^{-i_r} \right) \left(\prod_{r=1}^l x^{j_r} b x^{-j_r} \right) \left(\prod_{r=1}^n x^{m_r} a^2 x^{-m_r} \right),$$

where $i_1 < i_2 < \dots < i_k, j_1 < j_2 < \dots < j_l$, and $m_1 < m_2 < \dots < m_n$.

Proof. It follows from Lemma 2.4 and the group structure of Q_8 . □

Theorem 4.4. $\mathcal{G}_2(\mathcal{C}(Q_8))$ embeds into $\mathrm{GL}_6(\mathbb{Z}_2[t^{\pm 1}])$.

Proof. Let

$$\alpha : \{a, b, xax^{-1}, xbx^{-1}, x^2\} \rightarrow \mathrm{GL}_6(\mathbb{Z}_2[t^{\pm 1}])$$

be the function specified by

$$\begin{aligned} \alpha(a) &= \begin{pmatrix} 1 & t & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(b) &= \begin{pmatrix} 1 & 0 & t & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(xax^{-1}) &= \begin{pmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-1} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & t^{-1} + 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(xbx^{-1}) &= \begin{pmatrix} 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-1} \\ 0 & 0 & 1 & 0 & 0 & t^{-1} \\ 0 & 0 & 0 & 1 & 0 & t^{-1} \\ 0 & 0 & 0 & 0 & 1 & t^{-1} + 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(x^2) &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & t & 0 & 0 & 0 & 0 \\ 0 & 0 & t & 0 & 0 & 0 \\ 0 & 0 & 0 & t & 0 & 0 \\ 0 & 0 & 0 & 0 & t & 0 \\ 0 & 0 & 0 & 0 & 0 & t^2 \end{pmatrix}. \end{aligned}$$

Easily $\{\alpha(a), \alpha(b)\}$ and $\{\alpha(xax^{-1}), \alpha(xbx^{-1})\}$ generates copies of Q_8 . Next, we show that the map α may extend to a group homomorphism from $\mathcal{G}_2(\mathcal{C}(Q_8))$ to $\mathrm{GL}_6(\mathbb{Z}_2[t^{\pm 1}])$.

Simply extending α to generators of the torsion subgroup by conjugating by $\alpha(x^2)$, we then have

$$\begin{aligned} \alpha(x^{2n}ax^{-2n}) &= \begin{pmatrix} 1 & t^{-n+1} & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(x^{2n}bx^{-2n}) &= \begin{pmatrix} 1 & 0 & t^{-n+1} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n} \\ 0 & 0 & 1 & 0 & 0 & t^{-n} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(x^{2n+1}ax^{-2n-1}) &= \begin{pmatrix} 1 & t^{-n} & 0 & t^{-n} & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n-1} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & t^{-n-1} + t^{-n} \\ 0 & 0 & 0 & 0 & 1 & t^{-n} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \\ \alpha(x^{2n+1}bx^{-2n-1}) &= \begin{pmatrix} 1 & 0 & t^{-n} & 0 & t^{-n} & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n-1} \\ 0 & 0 & 1 & 0 & 0 & t^{-n-1} \\ 0 & 0 & 0 & 1 & 0 & t^{-n-1} \\ 0 & 0 & 0 & 0 & 1 & t^{-n-1} + t^{-n} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \end{aligned}$$

To show α extends to a group homomorphism, it suffices to check those relations in Theorem 1.1, or more precisely in our index two subgroup case, those identities in Lemma 2.3. Indeed, applying Lemma 4.2 where the assumptions can be easily verified in our case (multi-dimensional Heisenberg groups), it is straightforward that $\alpha(x^na x^{-n})$ commutes with $\alpha(x^m a x^{-m})$ and that $\alpha(x^n b x^{-n})$ commutes with $\alpha(x^m b x^{-m})$. Moreover, applying Lemma 4.2, we calculate

$$\begin{aligned} &[\alpha(x^{2n}ax^{-2n}), \alpha(x^{2m}bx^{-2m})] \\ &= \left[\begin{pmatrix} 1 & t^{-n+1} & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & t^{-m+1} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-m} \\ 0 & 0 & 1 & 0 & 0 & t^{-m} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \right] \end{aligned}$$

$$\begin{aligned}
&= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & t^{-m-n+1} \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \alpha([x^{2n}ax^{-2n}, x^{2m}bx^{-2m}]), \\
&[\alpha(x^{2n+1}ax^{-2n-1}), \alpha(x^{2m+1}bx^{-2m-1})] \\
&= \left[\begin{pmatrix} 1 & t^{-n} & 0 & t^{-n} & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n-1} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & t^{-n-1} + t^{-n} \\ 0 & 0 & 0 & 0 & 1 & t^{-n} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \right. \\
&\quad \left. \begin{pmatrix} 1 & 0 & t^{-m} & 0 & t^{-m} & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-m-1} \\ 0 & 0 & 1 & 0 & 0 & t^{-m-1} \\ 0 & 0 & 0 & 1 & 0 & t^{-m-1} \\ 0 & 0 & 0 & 0 & 1 & t^{-m-1} + t^{-m} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \right] \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & t^{-n-m} \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \alpha([x^{2n+1}ax^{-2n-1}, x^{2m+1}bx^{-2m-1}]), \\
&[\alpha(x^{2n}ax^{-2n}), \alpha(x^{2m+1}bx^{-2m-1})] \\
&= \left[\begin{pmatrix} 1 & t^{-n+1} & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & t^{-m} & 0 & t^{-m} & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-m-1} \\ 0 & 0 & 1 & 0 & 0 & t^{-m-1} \\ 0 & 0 & 0 & 1 & 0 & t^{-m-1} \\ 0 & 0 & 0 & 0 & 1 & t^{-m-1} + t^{-m} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \right] \\
&= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & t^{-n-m} \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \alpha([x^{2n}ax^{-2n}, x^{2m+1}bx^{-2m-1}]),
\end{aligned}$$

and

$$\begin{aligned}
 & [\alpha(x^{2n+1}ax^{-2n-1}), \alpha(x^{2m}bx^{-2m})] \\
 &= \left[\begin{pmatrix} 1 & t^{-n} & 0 & t^{-n} & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-n-1} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & t^{-n-1} + t^{-n} \\ 0 & 0 & 0 & 0 & 1 & t^{-n} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & t^{-m+1} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & t^{-m} \\ 0 & 0 & 1 & 0 & 0 & t^{-m} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \right] \\
 &= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & t^{-n-m} \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} = \alpha([x^{2n+1}ax^{-2n-1}, x^{2m}bx^{-2m}]).
 \end{aligned}$$

Therefore, the compatibility of α with the identities in Lemma 2.3 follows from the commutator identities in group theory (4.1).

Finally, we show the homomorphism α has trivial kernel. First note that any torsion free element does not lie in the kernel. Let γ be a torsion element in $\mathcal{G}(\mathcal{C}(Q_8))$. It has the normal form as in Lemma 4.3. Let $\alpha(\gamma) = (\alpha(\gamma)_{ij}) = I$, the identity matrix. $\alpha(\gamma)_{14} = 0$ implies that there are no odd conjugates of a in the normal form of γ . Then, $\alpha(\gamma)_{12} = 0$ implies that there are no conjugates of a in γ . Moreover, $\alpha(\gamma)_{15} = 0$ implies that there are no odd conjugates of b in γ and hence $\alpha(\gamma)_{13} = 0$ implies that there are no conjugates of b in γ . $\alpha(\gamma)_{16} = 0$ implies that there are no conjugates of a^2 in γ . So, $\alpha(\gamma) = I$ implies that γ is trivial. \square

Remark 4.5. Since virtually linear implies linear, then we have the linearity of $\mathcal{G}(\mathcal{C}(Q_8))$.

4.3. Linearity of $\mathcal{G}(\mathcal{C}(M_{2^n}))$. Now, we consider the Iwasawa/modular group M_{2^n} of order 2^n , $n \geq 3$, where

$$M_{2^n} = \langle a, b \mid a^{2^{n-1}} = b^2 = e, bab^{-1} = a^{2^{n-2}+1} \rangle.$$

It has center $Z(M_{2^n}) = \langle a^2 \rangle$ and derived subgroup $[M_{2^n}, M_{2^n}] = \langle a^{2^{n-2}} \rangle$. Actually, $G = \{1, a, a^2, \dots, a^{2^{n-1}-1}, b, ab, a^2b, \dots, a^{2^{n-1}-1}b\}$.

$\mathcal{G}(\mathcal{C}(M_{2^n})) = \langle a, b, x \rangle$. $\mathcal{G}_2(\mathcal{C}(M_{2^n})) = \langle a, b, xax^{-1}, xbx^{-1}, x^2 \rangle$ is a index two subgroup of $\mathcal{G}(\mathcal{C}(M_{2^n}))$.

Lemma 4.6. Any nontrivial torsion element of $\mathcal{G}(\mathcal{C}(M_{2^n}))$ can be uniquely written in the following form:

$$\prod_{r=1}^k x^{i_r} a^{s_r} x^{-i_r} \prod_{r=1}^l x^{j_r} b x^{-j_r} \prod_{r=1}^n x^{m_r} [a, b] x^{-m_r},$$

where $i_1 < i_2 < \dots < i_k, j_1 < j_2 < \dots < j_l, m_1 < m_2 < \dots < m_n$, and $1 \leq s_1, s_2, \dots, s_k \leq 2^{n-2} - 1$.

Proof. It follows from Lemma 2.4 and the group structure of M_{2^n} . \square

Theorem 4.7. $\mathcal{G}_2(\mathcal{C}(M_{2^n}))$ embeds into $\mathrm{GL}_{2^{n-1}+2}(\mathbb{Z}_2[t^{\pm 1}])$.

Proof. The idea of the proof is similar with the case of Q_8 .

Let $E_{i,j}$, $1 \leq i, j \leq 2^{n-1} + 2$, denote the $(2^{n-1} + 2) \times (2^{n-1} + 2)$ matrix with 1 in the i -th row j -th column and 0 everywhere else. $E_{i,i}$ is simply denoted by E_i .

Let α be the map from the generating set $\{a, b, xax^{-1}, xbx^{-1}, x^2\}$ to $\mathrm{GL}_{2^{n-1}+2}(\mathbb{Z}_2[t^{\pm 1}])$ satisfying:

$$\begin{aligned}\alpha(a) &= I + E_{1,2} + \sum_{m=1}^{2^{n-2}-2} E_{2m,2m+2} + E_{2^{n-1}-2,2^{n-1}+2} + E_{1,2^{n-1}}, \\ \alpha(b) &= I + E_{2^{n-1},2^{n-1}+2} + E_{2^{n-1}+1,2^{n-1}+2}, \\ \alpha(xax^{-1}) &= I + t^{-1} \sum_{m=1}^{2^{n-3}} E_{2m-1,2m+1} + \sum_{m=2^{n-3}+1}^{2^{n-2}-1} E_{2m-1,2m+1} \\ &\quad + E_{2^{n-1}-1,2^{n-1}+2} + t^{-2^{n-3}} E_{1,2^{n-1}+1}, \\ \alpha(xbx^{-1}) &= I + t^{-2^{n-3}} E_{2^{n-1},2^{n-1}+2} + E_{2^{n-1}+1,2^{n-1}+2}, \\ \alpha(x^2) &= E_1 + \sum_{m=1}^{2^{n-2}-1} (t^m E_{2m} + t^m E_{2m+1}) + t^{2^{n-3}} E_{2^{n-1}} + t^{2^{n-3}} E_{2^{n-1}+1} \\ &\quad + t^{2^{n-2}} E_{2^{n-1}+2}.\end{aligned}$$

It is easy to verify that $\alpha(a)$ has order 2^{n-1} and $\alpha(a)^{2^{n-2}} = I + E_{1,2^{n-1}+2}$. $\alpha(a)^m$, $2 \leq m \leq 2^{n-1}$, has at least $2^{n-1} - m$ nonzero entries above the diagonal. Indeed,

$$\begin{aligned}\alpha(a)^2 &= I + E_{1,4} + \sum_{m=1}^{2^{n-2}-3} E_{2m,2m+4} + E_{2^{n-1}-4,2^{n-1}+2}, \\ \alpha(a)^4 &= I + E_{1,8} + \sum_{m=1}^{2^{n-2}-5} E_{2m,2m+8} + E_{2^{n-1}-8,2^{n-1}+2}, \\ &\vdots \\ \alpha(a)^{2^j} &= I + E_{1,2^{j+1}} + \sum_{m=1}^{2^{n-2}-2^j-1} E_{2m,2m+2^{j+1}} + E_{2^{n-1}-2^j+1,2^{n-1}+2}, \\ &\vdots \\ \alpha(a)^{2^{n-3}} &= I + E_{1,2^{n-2}} + \sum_{m=1}^{2^{n-2}-2^{n-3}-1} E_{2m,2m+2^{n-2}} + E_{2^{n-1}-2^{n-2},2^{n-1}+2},\end{aligned}$$

$$\alpha(a)^{2^{n-2}} = I + E_{1,2^{n-1}+2},$$

$$\alpha(a)^{2^{n-1}} = I.$$

Moreover, we have similar properties with $\alpha(xax^{-1})$ because of similar construction:

$$\alpha(xax^{-1})^{2^{n-2}} = I + t^{-2^{n-3}} E_{1,2^{n-1}+2},$$

$$\alpha(xax^{-1})^{2^{n-1}} = I.$$

Applying Lemma 4.2 where the assumptions are easily verified, we see that

$$[\alpha(a), \alpha(b)] = I + E_{1,2^{n-1}+2} = \alpha(a)^{2^{n-2}},$$

$$[\alpha(xax^{-1}), \alpha(xbx^{-1})] = I + t^{-2^{n-3}} E_{1,2^{n-1}+2} = \alpha(xax^{-1})^{2^{n-2}}.$$

Since $\alpha(b)^2 = \alpha(xbx^{-1})^2 = I$, then $\{\alpha(a), \alpha(b)\}$ and $\{\alpha(xax^{-1}), \alpha(xbx^{-1})\}$ generates two copies of M_{2^n} .

Next, we show that α extends to a group homomorphism. Extending α , we have

$$\begin{aligned} \alpha(x^{2k}ax^{-2k}) &= I + t^{-k} E_{1,2} + t^{-k} \sum_{m=1}^{2^{n-2}-2} E_{2m,2m+2} \\ &\quad + t^{-k} E_{2^{n-1}-2,2^{n-1}+2} + t^{-2^{n-3}k} E_{1,2^{n-1}}, \\ \alpha(x^{2k}bx^{-2k}) &= I + t^{-2^{n-3}k} E_{2^{n-1},2^{n-1}+2} + t^{-2^{n-3}k} E_{2^{n-1}+1,2^{n-1}+2}, \\ \alpha(x^{2k+1}ax^{-2k-1}) &= I + t^{-1-k} \sum_{m=1}^{2^{n-3}} E_{2m-1,2m+1} + t^{-k} \sum_{m=2^{n-3}+1}^{2^{n-2}-1} E_{2m-1,2m+1} \\ &\quad + t^{-k} E_{2^{n-1}-1,2^{n-1}+2} + t^{-2^{n-3}(k+1)} E_{1,2^{n-1}+1}, \\ \alpha(x^{2k+1}bx^{-2k-1}) &= I + t^{-2^{n-3}(k+1)} E_{2^{n-1},2^{n-1}+2} + t^{-2^{n-3}k} E_{2^{n-1}+1,2^{n-1}+2}, \\ \alpha(x^k[a,b]x^{-k}) &= I + t^{-2^{n-3}k} E_{1,2^{n-1}+2}. \end{aligned}$$

Applying Lemma 4.2 where the assumptions are easily verified because of the alternating nonzero entries construction of $\alpha(a)$ and $\alpha(xax^{-1})$ and symmetricity of the formula in the lemma, we see that $\alpha(x^kax^{-k})$'s commute with each other, so do $\alpha(x^kbx^{-k})$'s. Moreover, we see that $\alpha(x^ka^2x^{-k})$'s commute with $\alpha(x^kbx^{-k})$'s and

$$\begin{aligned} [\alpha(x^{2k}ax^{-2k}), \alpha(x^{2l}bx^{-2l})] &= I + t^{-2^{n-3}(k+l)} E_{1,2^{n-1}+2} \\ &= \alpha(x^{k+l}[a,b]x^{-k-l}), \\ [\alpha(x^{2k+1}ax^{-2k-1}), \alpha(x^{2l}bx^{-2l})] &= I + t^{-2^{n-3}(k+l+1)} E_{1,2^{n-1}+2} \\ &= \alpha(x^{k+l+1}[a,b]x^{-k-l-1}), \\ [\alpha(x^{2k}ax^{-2k}), \alpha(x^{2l+1}bx^{-2l-1})] &= I + t^{-2^{n-3}(k+l+1)} E_{1,2^{n-1}+2} \\ &= \alpha(x^{k+l+1}[a,b]x^{-k-l-1}), \end{aligned}$$

$$\begin{aligned} [\alpha(x^{2k+1}ax^{-2k-1}), \alpha(x^{2l+1}bx^{-2l-1})] &= I + t^{-2^{n-3}(k+l+1)}E_{1,2^{n-1}+2} \\ &= \alpha(x^{k+l+1}[a, b]x^{-k-l-1}). \end{aligned}$$

Therefore, the compatibility of α with the identities in Lemma 2.3 follows from above calculations and commutator identities (4.1).

Finally, we show the homomorphism α has trivial kernel. Note that any torsion free element does not lie in the kernel. Let γ be a torsion element in $\mathcal{G}_2(\mathcal{C}(M_{2^n}))$. It has the normal form as in Lemma 4.6. Suppose $\alpha(\gamma) = I$. $\alpha(\gamma)_{1,2} = 0$ implies that there are no even conjugates of a^{2k-1} , $1 \leq k \leq 2^{n-3}$, in the normal form of γ . $\alpha(\gamma)_{1,3} = 0$ implies that there are no odd conjugates of a^{2k-1} , $1 \leq k \leq 2^{n-3}$, in γ . Moreover, $\alpha(\gamma)_{1,2^m} = 0$, $2 \leq m \leq n-2$, imply that there are no even conjugates of a^{2k-2} , $2 \leq k \leq 2^{n-3}$, in γ and $\alpha(\gamma)_{1,2^{m+1}} = 0$, $2 \leq m \leq n-2$, implies that there are no odd conjugates of a^{2k-2} , $2 \leq k \leq 2^{n-3}$, in γ . $\alpha(\gamma)_{2^{n-1}, 2^{n-1}+2} = \alpha(\gamma)_{2^{n-1}+1, 2^{n-1}+2} = 0$, implies that there are no conjugates of b in γ and $\alpha(\gamma)_{1, 2^{n-1}+2} = 0$ implies that there are no conjugates of $[a, b]$ in γ . Thus, $\alpha(\gamma) = I$ implies that γ is trivial. \square

Remark 4.8. As pointed out by L. Bartholdi, the linear representations given in this chapter are not optimal in the sense that they do not have the least degree. In the optimal case, we may lose the diagonal action of x^2 . It is suggested by the anonymous referee that it should be possible to give a more conceptual and general proof of linearity that covers all cases in Theorem 1.1, and that the representation should be sought in $\text{GL}(\mathbb{F}_2[H, t^{\pm 1}])$, where H is a subgroup of $\mathcal{G}(\mathcal{C}(G))$ generated by G and $x^{-1}Gx$.

Remark 4.9. M. Larsen asked whether or not F being a finite p -group is a necessary and sufficient condition for $\mathcal{G}(\mathcal{C}(F))$ to be linear over one field. We only know the necessity. Ju. E. Vapnè [18, 19] and, independently, B. A. F. Wehrfritz [21, 20] give necessary and sufficient conditions for a lamplighter group to be linear over some field. In particular, $\mathbb{Z}_p \wr \mathbb{Z}$ is only linear over characteristic p . Since $\mathcal{G}(\mathcal{C}(F))$ might contain copies of $\mathbb{Z}_p \wr \mathbb{Z}$, for different p 's, then F being a finite p -group is a necessary condition for $\mathcal{G}(\mathcal{C}(F))$ to be linear over some field. But this of course does not rule out the cases of embedding into a product of general linear groups over different fields.

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