ON GROUPS THAT HAVE NORMAL FORMS COMPUTABLE IN LOGSPACE

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Abstract. We consider the class of finitely generated groups which have a normal form computable in *logspace*. We prove that the class of such groups is closed under passing to finite index subgroups, direct products, wreath products, and certain free products and infinite extensions, and includes the solvable Baumslag-Solitar groups, as well as non-residually finite (and hence non-linear) examples. We define a group to be *logspace embeddable* if it embeds in a group with normal forms computable in logspace. We prove that finitely generated nilpotent groups are logspace embeddable. It follows that all groups of polynomial growth are logspace embeddable.

1. Introduction

Much of combinatorial, geometric and computational group theory focuses on computing efficiently in finitely generated groups. Recent work in group-based cryptography demands fast and memory-efficient ways to compute *normal forms* for group elements [12]. In this article we consider groups which have a normal form over some finite generating set, for which there is an algorithm to compute the normal form of a given input word in *logspace*. We show that the class of finitely generated groups having a logspace normal form is surprisingly large.

Definition 1. A *deterministic logspace transducer* consists of a finite state control and three tapes: the first *input tape* is read only, and stores the input word; the second *work tape* is read-write, but is restricted to using at most $c \log n$ squares, where n is the length of the word on the input tape and c is a fixed constant; and the third *output tape* is write-only, and is restricted to writing left to right only. A transition of the machine takes as input a letter of the input tape, a state of the finite state control, and a letter on the work-tape. On each transition the machine can modify the work tape, change states, move the input read-head, and write at most a fixed constant number of letters to the output tape, moving right along the tape for each letter printed.

Since the position of the read-head of the input tape is an integer between 1 and n, we can store it in binary on the work tape.

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Definition 2. Let X, Y be finite alphabets. Let X^* denote the set of all finite length strings in the letters of X, including the empty string λ. We call $f : X^* \to Y^*$ a *logspace computable function* if there is a deterministic logspace transducer that on input $w \in X^*$ computes $f(w)$.

Definition 3. A *normal form* L for a group G with finite symmetric generating set X is any subset of X^* that is in bijection with G under the map which sends a word w to the group element $\overline{w}$ which it represents.

Definition 4. A logspace computable function $f : X^* \to X^*$ for which $f(w)$ is the normal form word for w, is called a *logspace normal form function* for (G, X).

Definition 5. We say (G, X) has a *logspace normal form* if it has a logspace normal form function.

We may sometimes say a normal form is logspace computable without reference to a specific function.

As a simple first example, consider the infinite cyclic group $\langle a \mid - \rangle$ which has normal form $\{a^i \mid i \in \mathbb{Z}\}$. Let f be the function that converts a word w in the letters $a^{\pm 1}$ into normal form. Then f can be computed by scanning w from left to write updating a binary counter i, stored on the work tape, and when the end of the input is reached, output a i times if $i \geq 0$ or a^{-1} i times if $i < 0$. So the infinite cyclic group has a logspace normal form (with respect to the generating set $\{a, a^{-1}\}$).

The *word problem* asks for an algorithm for a finitely generated group which takes as input a word over the generating set, and decides whether or not the word is equal to the identity in the group. In [5] Lipton and Zalcstein proved that all linear groups (groups of matrices with entries from a field of characteristic zero) have word problem solvable in logspace. Since the class of linear group includes all free groups and all polycyclic groups, it follows from their results that the word problem for any such group can be decided in logspace. Simon extended this to linear groups over arbitrary fields [16].

One might expect the word problem to be computationally easier than computing a normal form. Certainly if one insists on a *geodesic* normal form (with respect to some generating set) then this is the case (see the end of this section).

The purpose of this article is to examine how broad the class of groups with normal forms computable in logspace is. In Section 2 we prove that free groups have logspace normal forms, a result which can be traced back to [6]. We then establish some basic properties of logspace normal forms, including the fact that having a logspace normal form is independent of finite generating set, and logspace normal forms can be computed in polynomial time. In Sections 3–5 we prove that the class of groups with logspace normal forms is closed under direct product, finite index subgroups and supergroups, finite quotients, and wreath product. It follows that finitely generated abelian groups, and the so-called *lamplighter groups*, belong to the class. In Sections 6–7 we prove that the class is closed under free product in certain cases and under certain infinite extensions, but in both of these contexts we must impose restrictions in order for our proofs to carry through. In Section 8 we present a normal form for solvable Baumslag-Solitar groups that can be computed in logspace. In Section 9 we define a group to be *logspace embeddable* if it is a subgroup of a group with logspace normal form, and prove various properties about the class of logspace embeddable groups, and in Section 10 we show that finitely generated nilpotent groups are logspace embeddable.

The problem of logspace *geodesic* normal forms is decidably more subtle, and in this article we focus on normal forms that are not necessarily length-minimal. In Section 5 we show that wreath products such as $\mathbb{Z} \wr \mathbb{Z}^2$ have logspace normal forms, and comment that the problem of computing a geodesic normal form for this group (with respect to the standard generating set) was shown to be NP-hard in [13], so the existence of a logspace geodesic normal form for this group seems unlikely. On the other hand many of the normal forms we present here, such as those for free groups described in Proposition 6 and free abelian groups described in Corollary 14, are geodesic. We prove in Proposition 12 that a logspace normal form has length no more than polynomial in the geodesic length. Recent work of Diekert, Kausch and Lohrey [2] extends the class of groups with logspace geodesic normal forms to right-angled Artin groups and right-angled Coxeter groups, and gives a partial result for general Coxeter groups.

It remains to see an example with polynomial time word problem that does not have a logspace normal form. Note that by [1] a group has word problem in NP if and only if it is a subgroup of a finitely presented group with polynomial Dehn function.

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2. Basic examples and properties of logspace normal forms

We begin with a key example of a class of groups with logspace normal form.

Consider the free group $\langle a_1, \dots, a_k \mid - \rangle$ of rank k with normal form the set of all freely reduced words over $X = \{a_1^{\pm 1}, \dots, a_k^{\pm 1}\}$. An obvious algorithm to convert a word in X^* would be to scan the word and when a canceling pair is read, delete it, step one letter back, and continue reading. A logspace function can only *read* the input, not write over it, so such an algorithm would not be logspace. Instead, the following algorithm makes use of the fact that free groups are linear, and so have logspace decidable word problem.

Proposition 6. *Let $\langle a_1, \dots, a_k \mid - \rangle$ be the free group of finite rank k with normal form the set of all freely reduced words over $X = \{a_i^{\pm 1}\}$. Then there is a logspace computable function $f : X^* \to X^*$ such that $f(w)$ is the normal form word for w.*

Proof. Fix two binary counters, c1 and c2 and set them both to 1.

(1) read the letter at position c1 of the input tape (call it x).
(2) scan forward to the next x^{-1} letter to the right of position c2, and set c2 to be the position of this x^{-1}.
(3) input the word from position c1 to c2 on the input tape into the logspace word-problem function for the free group of rank k.
  - if this function returns *trivial*, output nothing, set c1 = c2 + 1, and return to Step (1).
  - if it returns *non-trivial*, return to Step (2).
(4) if there is no next x^{-1} letter, write x to the output tape, set c1 = c1 + 1, and return to Step (1).

In other words, the algorithm reads x and looks for a subword xux^{-1} where u evaluates to the identity. If it finds such a subword, it effectively cancels it by not writing it to the output and moving forward to the next letter after xux^{-1}. If there is no such subword starting with x, then x will never freely reduce, so it outputs x, then repeats this process on the next letter after x on the input tape. □

This result can be traced back to [6]. The proof gives some indication of how one works in logspace. In Proposition 28 below we prove a more general result, that the class of groups with a normal form computable in logspace is closed under free products with logspace word problem.

The next lemma shows that logspace computable functions are closed under composition.

Lemma 7. *If $f, g : X^* \to X^*$ can both be computed in logspace, then their composition $f \circ g : X^* \to X^*$ can also be computed in logspace.*

Proof. On input a word $w \in X^*$, run the function f and when f calls for the jth input letter, run g on w but instead of outputting, each time g would write a letter, add 1 to a counter (in binary). Continue running g until the counter has value $j-1$, at which point, return the next letter g would output to f. □

Lemma 8. *In a group that has a logspace computable normal form function f, the following basic group operations can be performed in logspace:*

(1) *we can test whether two words represent the same group element;*
(2) *we can compute a normal form for the inverse of an element.*

Proof. To test equality, compute f on each word simultaneously and check that successive output letters are identical (without storing them). To compute the normal form for the inverse of an element, compose f with the (logspace) function that on input w, computes the length n of w in binary, then for $i = 1$ up to this length returns the formal inverse of the $(n-i+1)$th letter of w. □

One might expect that algorithms using a small amount of space do so at the expense of time, but it is well-known that this is not the case. To provide further context for the techniques employed in our proofs, we include here the standard proof that logspace algorithms run in polynomial time.

Lemma 9. *A deterministic logspace algorithm performs at most a polynomial number of steps.*

Proof. Define a *configuration* of a logspace transducer to be the contents of the work tape (which includes the position of the input tape read-head), and the current state of the finite state control. If the work tape has k allowable symbols, and the finite state control has d states, the total number of distinct configurations possible on input a word of length n is $dk^{c\log n} = O(n^c)$ where $c\log n$ is the maximum number of symbols the work tape contains. If the machine were to take more than $dk^{c\log n}$ steps, then it would be in the same configuration twice during the computation, and so would enter an infinite loop (since the machine is deterministic). The result follows. □

We next prove that the property of having a logspace normal form is invariant under change of finite generating sets.

Proposition 10. *Let X, Y be two finite symmetric generating sets for a group G. If (G, X) has a logspace normal form, then so does (G, Y).*

Proof. It suffices to show that adding or deleting a generator does not affect the existence of a logspace computable normal form function. Suppose that $Y = X \cup \{y, y^{-1}\}$, where $y \notin X$ and that $w_y \in X^*$ such that $\overline{w_y} = \overline{y}$. Let $f : Y^* \to X^*$ be the function that takes a word in Y^* to the word obtained by replacing each occurrence of y with the word w_y, and y^{-1} by the formal inverse of the word w_y. Notice that $\overline{f(u)} = \overline{f(v)}$ if and only if $\overline{u} = \overline{v}$, and that f can be computed in logspace.

We first suppose that g_X is a logspace computable normal form function, we let $g_Y = g_X \circ f$, and we show that g_Y is a logspace computable normal form function. By Lemma 7, g_Y is logspace computable, so we simply have to establish that it is a normal form function. Since f maps onto X^*, and since g_X is a normal form function, the natural map from $g_Y(Y^*)$ to G is onto. Let $u, v \in Y^*$ such that $g_Y(u) = g_Y(v)$. Since g_X is a normal form function, $\overline{f(u)} = \overline{f(v)}$ and hence $\overline{u} = \overline{v}$. Hence the natural map from $g_Y(Y^*)$ to G is injective. We have shown that g_Y is a normal form function.

We next suppose that g_Y is a logspace computable normal form function, we let $g_X = f \circ g_Y$. By Lemma 7, g_X is logspace computable, so we only have to show that g_X is a normal form function. Let $g \in G$. There exists a $v \in g_Y(Y^*)$ such that $\overline{v} = g$. Therefore, $\overline{f(v)} = g$ and hence the natural map from $g_X(X^*)$ to G is onto. Let $u, v \in X^*$ such that $g_X(u) = g_X(v)$. Then $f(g_Y(u)) = f(g_Y(v))$ so $\overline{g_Y(u)} = \overline{g_Y(v)}$. Since g_Y is a normal form function, $\overline{u} = \overline{v}$. Thus the natural map from $g_X(X^*)$ to G is injective. □

It will be convenient to assume that the normal form for the identity element is the empty string.

Proposition 11. *Let G be a group with finite symmetric generating set X, and let g_X be a normal form for G computable in logspace such that $g_X(\lambda) \neq \lambda$. Define a new normal form h_X for G which is identical to g_X except that for words representing the identity, $h_X(w) = \lambda$. Then h_X is logspace computable.*

Proof. Let $u = g_X(\lambda)$ be of length $m > 0$. Let $f : X^* \to X^*$ be the map sending u to λ and acting as the identity on all other words. Since m is a fixed constant, we can store the word u in a finite state control. Then f^* can be computed in logspace as follows: using a (binary) counter, scan the input word to compute its length; if it has length m, for $i = 1$ to m, check that the ith input letter is identical to the ith letter of u (stored in the finite state control); if it is, return λ, otherwise, move to the start of the input tape and write each letter on the input tape from left to right onto the output tape. Since $h_X = f \circ g_X$, by Lemma 7, h_X is also computable in logspace. □

The next proposition gives a restriction on what types of normal form languages can be calculated in logspace; namely, the length of the normal form is bounded by a polynomial in the length of the input.

Proposition 12. *If G has a normal form over X^* which can be computed in logspace, then there is a constant c such that the normal form for an input word of length n has length $O(n^c)$.*

Proof. Let p be the maximum length of a word written to the output tape in any one transition. (Note there are a finite number of possible transitions.) By Lemma 9, on input a word of length n, the computation takes a polynomial number of steps, $O(n^c)$, and in each step at most p letters can be written to the output tape, so the maximum length of the output normal form word is $O(pn^c)$. $\square$

3. Closure under direct product

Proposition 13. *The set of groups with logspace normal forms is closed under direct product.*

Proof. Let G and H be groups with symmetric generatoring sets X and Y, and with logspace normal form functions g_X and h_Y respectively. We may assume that X and Y are disjoint; let Z be their disjoint union. Then Z is a finite set of symmetric generators for $G \times H$. Define $k_Z : Z^* \to Z^*$ as follows. Let w be a word in Z^*. Then there exist words $u \in X^*$ and $v \in Y^*$ such that w consists of u and v interleaved. We let $k_Z(w) = g_X(u)h_Y(v)$. Note that $k_Z(Z^*)$ comprises a unique set of representatives for $G \times H$. We can compute k_Z in logspace: read w once, ignoring all letters from Y and computing $g_X(u)$; read w again, ignoring all letters from X and computing $g_Y(v)$. $\square$

Corollary 14. *All finitely generated abelian groups have logspace normal form functions. In the case of $\mathbb{Z}^n$, if $t_1, t_2, \ldots, t_n$ is a set of free generators, the normal forms are of the form $t_1^{\alpha_1} t_2^{\alpha_2} \ldots t_n^{\alpha_n}$ with $\alpha_i \in \mathbb{Z}$.*

Proof. The result follows from Propositions 13 and 6. $\square$

4. Closure under passing to finite index subgroups and supergroups

Let G and H be finitely generated groups with G a finite index subgroup of H. The goal of this section is to show that G has logspace normal form if and only H does. To do so, we will show that the standard Schreier rewriting process for H is logspace computable, and from this our desired result will follow easily.

We define a *rewriting process* for G in the usual way (see, for example, [9]):

Definition 15. Let H be a group generated by a finite symmetric generating set Y. Let G be a subgroup of H, and let $W = \{w_1, w_2, \ldots, w_m\}$ be a set of words over Y that generate G. Let S be the set of words over Y that represent elements of G. Let $X = \{x_1, x_2, \ldots, x_m, x_1^{-1}, x_2^{-1}, \ldots, x_m^{-1}\}$ be a new alphabet (disjoint from Y), which we take to be a generating set for G via the map that sends x_i to w_i and x_i^{-1} to w_i^{-1} (the formal inverse of w_i). A *rewriting process for G with respect to W* is a mapping τ from S to X^* such that for all words $u \in S$, u and $\tau(u)$ represent the same element of G.

When G has finite index in H, a set W of *standard Schreier representatives* of words over Y that generate G can be defined as follows. Fix a set R of words over Y whose images in H form a set of right coset representatives for G. For all $r \in R$ and $y \in Y$, let $g_{r,y}$ be the word in S given by $g_{r,y} = ryq^{-1}$, where $q \in R$ represents the coset $G\overline{ry}$. Then the set $W = \{g_{r,y} \mid r \in R, y \in Y\}$ generates G (see, for example, p. 89 of [9]).

The Schreier rewriting process for G with respect to these generators can be described as follows. Consider the Schreier graph for G in H (in which vertices are labeled with the coset representatives from R and edges are labeled with generators from Y). For a given word $w \in S$, initialize $\tau(w)$ to λ. Trace w through the Schreier graph. When traversing an edge from r labeled y, update $\tau(w)$ to be $\tau(w)g_{r,y}$. Then τ is a rewriting process for H with respect to the Schreier generators (see, for example, p. 91 of [9]). Since our sets R and W and the Schreier graph can all be stored in a finite amount of space, it is clear that τ can be computed in logspace.

Proposition 16. *Let G, H be finitely generated groups with G a finite index subgroup of H. Then H has logspace normal form if and only if G has logspace normal form.*

Proof. Throughout this proof we use the notation established above. We begin by assuming that H has logspace normal form h. We define our normal form g for G as follows. Each word w over X can be transformed into a word w' over Y by replacing the each occurrence of a letter x_i with the corresponding word w_i from W, and by replacing each occurrence of a letter x_i^{-1} with the formal inverse of the word w_i. Then $g(w)$ can be defined to be $\tau(h(w'))$. Since h and τ can both be computed in logspace, by Lemma 7, so can g.

Next we assume that G has logspace normal form g. For a word w over Y, we define $h(w)$ to be $g(w')r$, where r is the word in R representing the coset $G\overline{w}$ and $w' = wr^{-1}$. To compute $h(w)$ in logspace, we trace w in the Schreier graph to compute and store r. We then call the normal form function g. When it asks for the ith letter we supply it with the ith letter of wr^{-1}. When it asks to output a letter, we do so. Finally we output r. □

5. Closure under wreath product

In this section we prove that the property of having a logspace normal form is closed under restricted wreath products. Propositions 10 and 11 allow us to assume from now on that generating sets contain only non-trivial elements, and if f_X is a logspace normal form function over a generating set X then $f_X(\lambda) = \lambda$.

Definition 17. Given an ordered alphabet X, let $\leq_{SL}$ denote the short-lex ordering on X^*.

Lemma 18. *Let G be a group with symmetric generating set X and logspace normal form function f_X. The short-lex order of the normal form of two words in X^* is logspace computable.*

Proof. Let $(u, v) \in X^* \times X^*$ be given. We need to decide whether

- $f_X(u) = f_X(v)$,
- $f_X(u) <_{SL} f_X(v)$, or
- $f_X(v) <_{SL} f_X(u)$.

We first call f_X on u, but rather than write any output, each time a letter would be written to the output tape, we increase a counter, stored in binary. We then do the same for v and compare the two counters, if $|f_X(u)| < |f_X(v)|$ or $|f_X(v)| < |f_X(u)|$ we are done.

If not, call f_X on u and v simultaneously to obtain the first letter of each output. If the letters are the same, obtain the next letter. As soon as we encounter an i for which the ith letters do not agree, we can deduce which word is greater in the short-lex ordering, and if not, we deduce that $f_X(u) = f_X(v)$. □

We now establish some notation that will be useful in defining our normal form for $G \wr H$. Let $G = \langle X \rangle$ and $H = \langle Y \rangle$ be groups with logspace normal form functions f_X and f_Y respectively. We may assume that X and Y are disjoint, finite symmetric generating sets.

Let $w \in (X \sqcup Y)^*$. We will use $X(w)$ to denote the word in X^* obtained by deleting all letters not in X from w, and similarly for $Y(w)$. For $w = a_1 a_2 \dots a_n$, $a_j \in X \sqcup Y$, and $1 \leq i \leq n$, we will let $X(i,w)$ (or $Y(i,w)$) denote the word $X(a_1 a_2 \dots a_i)$ (or $Y(a_1 a_2 \dots a_i)$). For convenience, set $X(0,w) = \lambda$ and $Y(0,w) = \lambda$. Note that $X(i,w)$ (and $Y(i,w)$) are computable in logspace: if $w = a_1 \dots a_n$, set $j = 0$; while $j < i$, increment j by 1 and if $a_j \in X$, output a_j.

Define $V(w) = \{f_Y(Y(s,w)) \mid 0 \leq s \leq n\}$. Then $V(w)$ is a finite set of strings of Y^*. Note that $\lambda = f_Y(Y(0,w))$ is the shortest element in $V(w)$. Set $v_0 = \lambda$. The next lemma tells us how to compute the next element of $V(w)$ in shortlex order in logspace, assuming the word w is written on the input tape. First, we need a way to store a word in $V(w)$ without using too much space, so to store a word in $V(w)$ corresponding to the element represented by $Y(i,w)$, we merely store the value i. To recover the word v_i, we run f_Y on the word $Y(i,w)$.

Lemma 19. *Let $w = a_1 \dots a_n \in (X \sqcup Y)^*$ be written on an input tape, and $V(w) = \{f_Y(Y(s,w)) \mid 0 \leq s \leq n\}$. There is a logspace function which, given an integer p such that $Y(p,w) = v_i$, computes q such that $Y(q,w) = v_{i+1}$ where v_{i+1} is the next largest word from v_i in shortlex order, or returns that v_i is the largest word in $V(w)$.*

Proof. Feed $(Y(p,w), Y(1,w))$ into the algorithm in Lemma 18, and if

$$f_Y(Y(p,w)) <_{SL} f_Y(Y(1,w)),$$

set $q = 1$. So q encodes a word from $V(w)$ that is larger in the shortlex ordering than v_i encoded by p.

For each $2 \leq j \leq n$, read a_j, and if $a_j \in Y$, feed $(Y(p,w), Y(j,w))$ into the algorithm in Lemma 18. If $Y(j,w)$ is larger than $Y(p,w)$, check to see if q has been assigned a value. If not, set $q = j$. If q already has a value, feed $(Y(q,w), Y(j,w))$ into the algorithm in Lemma 18. If $Y(j,w)$ is shorter than $Y(q,w)$, set $q = j$. So q encodes an element in $V(w)$ that is greater that v_i and less than the previous $Y(q,w)$.

When every j up to n has been checked, if q has not been assigned a value, then v_i is the largest word in $V(w)$. Otherwise q encodes the next largest word $v_{i+1} = Y(q,w)$. □

Definition 20 (Normal form for $G \wr H$)**.** Let $w = a_1 \dots a_n \in (X \sqcup Y)^*$. Then

$$f_{X \sqcup Y}(w) = u_1^{v_1} u_2^{v_2} \dots u_k^{v_k} f_Y(Y(w)),$$

where $v_i \in f_Y(Y^*)$ with $v_i <_{SL} v_{i+1}$ and $u_i \in f_X(X^*)$, $u_i \neq \lambda$. (Note that by $u_i^{v_i}$ we mean $v_i u_i f_Y(v_i^{-1})$. Lemma 8 says $f_Y(v_i^{-1})$ can be computed in logspace if f_Y can.)

The words v_i correspond to elements of H for which the factor of $\bigoplus_{h \in H} G_h$ is non-trivial, so the v_is are a subset of $V(w)$. The words u_i correspond to the non-trivial element of G at each position v_i in H. The prefix of the normal form word does the job of moving to each position in H and fixing the value of G at that position. The shortlex ordering of $V(w)$ allows us to do this in a canonical way for any word representing an element of $G \wr H$. The suffix $f_Y(Y(w))$ takes us from the identity of H to the final position in H.

Since we know how to compute the v_i in shortlex order from Lemma 19, all we need now is to compute the u_i at each position.

Lemma 21 (Algorithm to compute u_i)**.** *Let $w = a_1 \dots a_n \in (X \sqcup Y)^*$ be written on an input tape, $V(w) = \{f_Y(Y(s,w)) \mid 0 \leq s \leq n\}$, and p an integer such that $Y(p,w) = v_i \in V(w)$. There is a logspace function that decides whether the element of G in the factor corresponding to v_i in $\bigoplus_{h \in H} G_h$ is non-trivial, and a logspace function that outputs the normal form f_X of this element.*

Proof. Define a function $g_{X \sqcup Y} : (X \sqcup Y)^* \to X^*$ which computes a word in X^* equal to the element of G in the factor corresponding to $v_i = Y(p,w)$ in $\bigoplus_{h \in H} G_h$ as follows.

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(1) compute the length $n$ of $w$ and store it in binary.
(2) set a counter $l = 0$.
(3) while $l < n$:
      • call the function in Lemma 18 on $Y(p,w)$ and $Y(l,w)$ to decide if they
        are equal or not. If they are equal, set a boolean variable $b$ to be true,
        and otherwise set it to false.
      • while $l < n$ and the letter at position $l+1$ is in $X$:
          – if $b$ is true, print the letter at position $l+1$ to the output tape
          – increment $l$ by 1.
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Since the function in Lemma 18 is logspace then so is $g_{X \sqcup Y}$. The algorithm works by scanning the input word from left to right, and outputting only those letters from $X(w)$ that are in the factor corresponding to v_i in $\bigoplus_{h \in H} G_h$.

Then $f_X \circ g_{X \sqcup Y}$ will output the normal form word in X^* for the element of X in the copy of G corresponding to the element $v_i \in H$. To decide if this element is trivial or not, run the above procedure and test whether the output is λ or not. □

Theorem 22. *The normal form function $f_{X \sqcup Y}$ for $G \wr H$ can be computed in logspace.*

Proof. Set $p = 0$ (so $Y(p,w) = v_0 = \lambda$, the shortest element in $V(w)$). Set a boolen variable max to be false. While max is false:

- use Lemma 21 to determine whether the element in G at $Y(p,w)$ is non-trivial. If it is, output $f_Y(Y(p,w)) = v_i$. Then output u_i by running the algorithm in Lemma 21 again. Then output $f_Y(v_i^{-1})$ (apply Lemma 8 to function that computes $f_Y(Y(p,w))$).
- run the algorithm Lemma 18 with input p. If the algorithm returns that $Y(p,w)$ is maximal in $V(w)$, set the variable max to be true. Otherwise it finds q such that $Y(p,w) = v_i$ and $Y(q,w) = v_{i+1}$. Set $p = q$.

Finally, output $f_Y(Y(w))$. □

It follows that the class of groups with logspace normal form includes the so-called *lamplighter groups*, and the group $\mathbb{Z} \wr \mathbb{Z}^2$ (which Parry considered in [13], showing with respect to a standard generating set finding a geodesic form for a given word is NP-hard, and so a geodesic normal form for it is unlikely to be logspace computable).

In [17] Waack gives an example of a group with logspace word problem that is not residually finite, and hence non-linear. Theorem 22 allows us to construct non-linear and non-residually finite groups having logspace normal forms.

Corollary 23. *Not all groups with a logspace normal form are linear.*

Proof. By Corollary 15.1.5 in [14], $(\mathbb{Z} \wr \mathbb{Z}) \wr \mathbb{Z}$ is not linear, but it has a logspace normal form by Theorem 22. $\square$

Corollary 24. *Not all groups with logspace normal forms are residually finite.*

Proof. Let G be the wreath product of the symmetric group S_3 on three letters and $\mathbb{Z} = \langle t \rangle$. By Theorem 22, G has logspace normal form. But it is easy to show that G is not residually finite. Let θ be a homomorphism from G to a finite group. We will show that θ kills the commutator subgroup $[S_3, S_3]$. Let n be a positive integer such that $t^n\theta = 1$. Since $[S_3, S_3^{t^n}] = 1$,

$$[S_3, S_3]\theta = [S_3\theta, (S_3^{t^n})\theta] = [S_3, S_3^{t^n}]\theta = 1.$$

$\square$

6. Closure under free products

Unfortunately we are not able to prove closure of logspace normal forms under free product in general, but we are able to do so if the free product has logspace word problem, for example if it is a free product of linear groups.

Let $G = \langle X \rangle$ and $H = \langle Y \rangle$ be groups with logspace normal form functions g_X and h_Y, and suppose X and Y are disjoint. By Proposition 11 we can assume that g_X and h_Y both have the property that the normal form for a word representing the identity is λ. We will define a normal form function for the free product $G * H$, which is generated by $X \sqcup Y$.

We start with the following lemma.

Lemma 25. *Let $w = u_1v_1u_2v_2 \dots u_kv_k$ where $u_i \in X^*$ and $v_i \in Y^*$. Then w represents an element in G if and only if $wu_k^{-1}u_{k-1}^{-1} \dots u_1^{-1} =_{G*H} 1$.*

Proof. We proceed by induction on k. For $k = 1$ we have $u_1v_1 \in G$ meaning $v_1 \in G$, but since $v_1 \in Y^*$ with Y disjoint from X, we must have $v_1 = 1$, so $u_1v_1u_1^{-1} = 1$.

Assume the result is true for k, and let $w = u_1v_1 \dots u_{k+1}v_{k+1}$ represent an element in G. By the Normal Form Theorem for free products ([7], p. 175), w has a unique reduced form consisting of a single subword $u \in X^*$, so we must have $u_i = 1$ for some $i > 1$ or $v_i = 1$ for some $i < k + 1$. If $u_i = 1$ then

$$w = u_1v_1 \dots u_{i-1}(v_{i-1}v_i)u_{i+1} \dots v_{k+1}$$

and by the induction hypothesis

$$wu_{k+1}^{-1}u_k^{-1} \dots u_{i+1}^{-1}u_{i-1}^{-1} \dots u_1^{-1} = 1.$$

Similarly if $v_i = 1$.

The converse is clearly true. $\square$

We define a normal form for $G * H$ recursively as follows.

Definition 26 (Normal form for $G * H$)**.** Let $w \in (X \sqcup Y)^*$.

(1) write w as a freely reduced word.
(2) if $\overline{w} \in G$, then define $f_{X \sqcup Y}(w) = g_X(X(w))$.

(3) if $\overline{w} \in H$, then define $f_{X \sqcup Y}(w) = h_Y(Y(w))$.
(4) otherwise, let w_1 be the longest initial segment of w such that $\overline{w_1} \in G$, and let w' be the tail of w, so $w = w_1 w'$. Then
   - if w_1 has nonzero length, define
$$f_{X \sqcup Y}(w) = g_X(X(w_1)) f_{X \sqcup Y}(w').$$
   - otherwise, let w_2 be the longest initial segment of w such that $\overline{w_2} \in H$, and let w' be the tail of w, so $w = w_2 w'$. Note that if $w_2 = \lambda$ then the first case applies, so w_2 has nonzero length.
   In this case, define
$$f_{X \sqcup Y}(w) = h_Y(Y(w_2)) f_{X \sqcup Y}(w').$$

Proposition 27. *The normal form function $f_{X \sqcup Y}$ is well defined.*

Proof. In case (1), by the previous lemma we have $w =_{G*H} X(w)$ (the word obtained from w by deleting all letters from Y). So the normal form function g_X applies and gives a unique representative for w. Similarly for case (2). So words that lie completely in one of the factors have a well-defined normal form.

Now let $w \in (X \sqcup Y)^*$ be freely reduced, and assume $\overline{w} \notin G$ and $\overline{w} \notin H$. Then $\overline{w}$ is non-trivial (since it is not in G or H). For each non-identity element of $G * H$, there is a unique way to represent it as an alternating product of non-identity elements in G and H [7]. So write $w =_{G*H} u_1 v_1 u_2 v_2 \ldots u_k v_k$ where $u_i \in X^*$ and $v_i \in X^*$. Since $\overline{w}$ does not lie in G or H, it has at least two factors.

If the alternating product starts with $u_1 \in X^*$, then we claim that any word representing $\overline{w}$ has a longest initial segment that evaluates to an element of G, and this element is equal to u_1. If so, then the choice made by $f_{X \sqcup Y}$ is unique. Take the (freely reduced) word w and write it as $a_1 b_1 \ldots a_l b_l$ with $a_i \in X^*$ and $b_i \in Y^*$ with only a_1, b_l allowed to be empty words. Then $v_k^{-1} u_k^{-1} \ldots v_1^{-1} u_1^{-1} a_1 b_1 \ldots a_l b_l =_{G*H} 1$, so by the normal form theorem [7] some term must represent the identity in G or H, and this term must involve u_1. So w has a prefix which is equal to u_1, and since $\overline{w} \notin G$, v_1 is not empty, so there is a longest prefix of w that equals u_1, and cancels so that v_1 can then cancel.

A similar argument applies if the alternating product starts with $v_1 u_2$. □

In Proposition 6 we proved that free groups of finite rank have logspace normal form, using the fact that they have logspace word problem. We generalise this argument to show that the function $f_{X \sqcup Y}$ can be computed in logspace, provided the word problem for $G * H$ can be decided in logspace.

Proposition 28. *Let $G = \langle X \rangle$ and $H = \langle Y \rangle$ be groups with logspace normal forms. Suppose furthermore that $G * H$ has logspace decidable word problem. Then $G * H$ has logspace normal form.*

Proof. Let $w \in (X \sqcup Y)^*$ be the freely reduced word equal to the input word (run the logspace algorithm in Proposition 6 on the input word to obtain it). By Lemma 25 we can compute j such that $w_1 = u_1 v_1 u_2 v_2 \ldots v_{j-1} u_j$ is the longest initial segment of w such that $\overline{w_1} \in G$, by inputting $u_1 v_1 u_2 v_2 \ldots v_{j-1} u_{j-1}^{-1} \ldots u_1^{-1}$ into the logspace word problem function for $G * H$.

Output the normal form g_X for $u_1 u_2 \ldots u_j$ and move the input pointer to point to v_j. For ease of notation, we rename $v_j u_{j+1} v_{j+1} \ldots u_k v_k$ to be our new w, and reindex so that $w = v_1 u_1 v_2 u_2 \ldots v_r u_r$. Compute j such that $w_1 = v_1 u_1 v_2 u_2 \ldots u_{j-1} v_j$

is the largest initial segment of our new w such that $\overline{w_1} \in H$. Output the normal form over Y for $v_1u_1v_2u_2 \dots u_{j-1}v_j$ and move the input pointer to point to u_j. Continue in this way until the entire input has been processed. Note that at any one stage we are only storing a constant number of pointers to the input. □

Corollary 29. *Let F be a field, and let G and H be linear over F with a logspace normal form. Then $G * H$ is also linear over F and it also has a logspace normal form.*

Proof. The class of groups which are linear over F is closed under free products (see, for example, Corollary 2.14 in [18]). All linear groups groups have logspace word problem (for the case when the characteristic of F is 0, see [5]; for the positive characteristic case see [16]). The corollary follows. □

7. Closure under infinite extensions

In this section we prove that certain infinite extensions of groups with logspace normal forms also have logspace normal form. If N is a normal subgroup of finitely generated group $G = \langle X \rangle$, if G/N has logspace normal form, and if there is a logspace computable function to produce normal forms for elements of N in terms of generators in X, then G has logspace normal form. This will enable us to extend our class to include certain amalgamated products and one-relator groups.

Notice that for the following lemma, N need not be finitely generated, and we posit the existence of a function similar to a normal form function for N in the sense that it produces unique representatives for the elements of N, but different in the sense that it is defined on words over the generators for the ambient group G.

Lemma 30. *Let G be a group with normal subgroup N. Let X be a finite symmetric generating set for G. Let $S = \{w \in X^* \mid \overline{w} \in N\}$. Suppose that*

- *G/N has logspace normal form; and*
- *there is a logspace computable function $f : S \to S$ such that $\overline{f(w)} = \overline{w}$ and $f(w_1) = f(w_2)$ if and only if $\overline{w_1} = \overline{w_2}$.*

Then G has logspace normal form.

Proof. Let $X_N = \{xN \mid x \in X\}$ be a generating set for G/N, and let $h : (X_N)^* \to (X_N)^*$ be the logspace normal form function for G/N with respect to this generating set. Define two logspace functions $p : X^* \to (X_N)^*$ and $q : (X_N)^* \to X^*$ by $p(x) = xN$ for each $x \in X$, and $q(xN) = x$ for each $xN \in X_N$. Let $\iota : X^* \to X^*$ be the logspace function $\iota(a_1 \dots a_n) = a_n^{-1} \dots a_1^{-1}$ that computes the inverse of a word.

Define a function $g : X^* \to X^*$ as follows: On input $w \in X^*$:

(1) compute $q(h(p(w)))$ writing the output word $b_1 \dots b_k$ to the output tape, storing the integer k
(2) call the function f, and when it asks for the ith input letter:
   - if $i \leq k$, call $\iota(q(h(p(w))))$ and return the ith letter of its output;
   - if $i > k$, return the $(i-k)$th letter of w.

Since $w \in wN$, step (1) of the algorithm computes $b = b_1 \dots b_k$ such that $wN = (b_1N) \dots (b_kN)$ and returns the letters $b_1, \dots, b_k$. Then $w = bn$ for some $n \in N$, and since $n = b^{-1}w$, step (2) of the algorithm outputs $f(b^{-1}w)$. □

We first explore some implications of Lemma 30 for amalgamated products. We are grateful to Chuck Miller for his invaluable input into the remainder of this section.

Corollary 31. *Suppose that G has logspace normal form, and that N is a normal subgroup such that G/N is linear and has logspace normal form. Then the amalgamated product H of G with itself along N has logspace normal form.*

Proof. Fix a finite generating set X for G, and define two new copies X_1 and X_2 of X as follows: for each element $x_j \in X$ make two new generators $(x_j)_1$ and $(x_j)_2$, and for $i = 1, 2$, let $X_i = \{(x_j)_i \mid x_j \in X\}$. Let G_1 and G_2 be two copies of G with generators X_1 and X_2 respectively, and let N_1 and N_2 be corresponding normal subgroups of G_1 and G_2.

We have $H/N = G_1/N_1 * G_2/N_2$ where G_i/N_i is linear and has logspace normal form. Hence by Corollary 29, H/N has logspace normal form, with respect to the generating set $X_1 \sqcup X_2$.

Let S be the set of words w over $X_1 \sqcup X_2$ such that $\overline{w} \in N$. Write $w \in S$ as an alternating product of subwords from X_1 and X_2. Since $\overline{w} \in N$, w is equal in H to a word $u \in X_1^*$ with $\overline{u} \in N_1$. Then $wu^{-1} = 1$ in H. Write wu^{-1} as an alternating product $u_1v_1 \dots u_kv_k$ with $u_i \in X_1^*, v_i \in X_2^*$ (with all subwords nonempty except possibly u_1 and v_k). By the normal form theorem for amalgamated free products [7], the alternating word contains a subword $u_i \in X_1^*$ with $\overline{u_i} \in N$, or $v_i \in X_2^*$ with $\overline{v_i} \in N$. In the first case write u_i as a word in X_2^* by replacing each $(x_j)_1$ letter by $(x_j)_2$, and v_i as a word in X_1^* by replacing each $(x_j)_2$ letter by $(x_j)_1$ in the second case. The resulting word is also equal to 1 in H, so if it contains letters from both generating sets, another subword can rewritten, reducing the number of alternating subwords, so that after a finite number of iterations the word wu^{-1} is equal in H to a word obtained by replacing all letters $(x_j)_2$ by $(x_j)_1$.

It follows that w is equal in H to the word obtained from w by replacing each $(x_j)_2$ letter by $(x_j)_1$. Let $p : (X_1 \sqcup X_2)^* \to (X_1 \sqcup X_2)^*$ be the map that performs this substitution, so clearly p can be computed in logspace, and $\overline{p(w)} = \overline{w}$ for all $w \in S$. Let g_{X_1} be the logspace normal form function for G_1 (since G has logspace normal form it follows that G_1 does). Then $f = g_{X_1} \circ p$ is logspace computable by Lemma 7.

Since $\overline{p(w)}$ is equal to $\overline{w}$ in H, and g_{X_1} is a normal form function, we have $\overline{f(w)} = \overline{w}$. If $f(u) = f(v)$ then $g_{X_1}(p(u)) = g_{X_1}(p(v))$, so $\overline{p(u)} = \overline{p(v)}$ since g_{X_1} is a normal form function, which implies $\overline{u} = \overline{v}$. Since we have satisfied the criteria of Lemma 30, the result follows. □

Corollary 32. *Let F be the free group on two generators. Then the amalgamated product of F with itself along the commutator subgroup has logspace normal form.*

Proof. The abelianization of F is a free abelian group, and hence is linear and has logspace normal form. □

Corollary 33. *Let* $\mathrm{BS}(1, p)$ *be a Baumlag-Solitar group (as defined in Section 8). Then the amalgamated product of* $\mathrm{BS}(1, p)$ *with itself along the commutator subgroup has logspace normal form.*

Proof. The abelianization of $\mathrm{BS}(1, p)$ is cyclic, and hence is linear and has logspace normal form. □

We next explore some implications of Lemma 30 for torus knot groups.

Lemma 34. *Let $G = \langle a, b \mid a^m = b^n \rangle$, where m and n are positive integers, and let N be the subgroup of G generated by a^m. Let*

$$w = a^{r_1} b^{s_1} a^{r_2} b^{s_2} \dots a^{r_k} b^{s_k}$$

such that $\overline{w} \in N$. Then m divides $\sum_{j=1}^{k} r_j$, n divides $\sum_{j=1}^{k} s_j$, and $\overline{w} = \overline{a^{mi}}$, where

$$i = \frac{1}{m} \sum_{j=1}^{k} r_j + \frac{1}{n} \sum_{j=1}^{k} s_j.$$

Proof. We proceed by induction on k. The case when $k = 1$ is clear. Assume that $k > 1$ and that our result holds for $k - 1$. Then by the Normal Form Theorem for Free Products with Amalgamation ([7], Theorem 2.6) either m divides r_i for some i, or n divides s_i for some i. Let us assume the latter, the argument being the same in either case. Since $\overline{b^{s_i}}$ is central, we may assume that

$$w = a^{r_1} b^{s_1} a^{r_2} b^{s_2} \dots b^{s_{i-1}} a^{r_i + r_{i+1}} b^{s_{i+1}} \dots a^{r_k} b^{s_k + s_i}.$$

Our result now follows from our inductive assumption. □

Corollary 35. *The torus knot group $G = \langle a, b \mid a^m = b^n \rangle$ for m, n positive integers has logspace normal form.*

Proof. Let N be the subgroup of G generated by a^m, which is normal since N is central. G/N is the free product of two finite cyclic groups, so by Corollary 29, it has a logspace normal form function. Let S be the set of words representing elements of N. Let $f : S \to S$ be the function that takes a word in S to its representative of the form a^{mi}. By Lemma 34 we can calculate f using two counters. This can be done in logspace. The result then follows from Lemma 30. □

Note that the braid group on three strands has presentation $\langle a, b \mid a^2 = b^3 \rangle$. Since braid groups on n strands are linear, it would be interesting to know whether or not they admit logspace normal forms for $n > 3$. We thank Arkadius Kalka for pointing this out.

8. Solvable Baumslag-Solitar groups

Let $G = \langle a, t \mid tat^{-1} = a^p \rangle$ for $p \geq 2$, and $X = \{a^{\pm 1}, t^{\pm 1}\}$. Note that G is isomorphic to the set of all matrices of the form

$$\begin{pmatrix} p^i & m \\ 0 & 1 \end{pmatrix},$$

where $i \in \mathbb{Z}$ and $m \in \mathbb{Z}[\frac{1}{p}]$, where the isomorphism is given by

$$t \to \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}, \ a \to \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}.$$

We obtain a normal form as follows. Write

$$\begin{pmatrix} p^i & m \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & m \\ 0 & 1 \end{pmatrix} \begin{pmatrix} p^i & 0 \\ 0 & 1 \end{pmatrix}.$$

Then $m \in \mathbb{Z}[\frac{1}{p}]$ has a unique p–ary expansion as either

- 0,
- $\frac{\eta_0}{p^{\alpha_0}} + \frac{\eta_1}{p^{\alpha_1}} + \dots + \frac{\eta_k}{p^{\alpha_k}}$ with $0 < \eta_j < p$ and $\alpha_0 > \alpha_1 > \dots > \alpha_k$, or

- $\frac{\eta_0}{p^{\alpha_0}} + \frac{\eta_1}{p^{\alpha_1}} + \cdots + \frac{\eta_k}{p^{\alpha_k}}$ with $-p < \eta_j < 0$ and $\alpha_0 > \alpha_1 > \cdots > \alpha_k$

where the p–ary expansion for m is written from least to most significant bits. Finally note that

$$\begin{pmatrix} 1 & \frac{\eta_j}{p^{\alpha_j}} \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \frac{1}{p^{\alpha_j}} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \eta_j \\ 0 & 1 \end{pmatrix} \begin{pmatrix} p^{\alpha_j} & 0 \\ 0 & 1 \end{pmatrix} = t^{-\alpha_j} a^{\eta_j} t^{\alpha_j},$$

so it follows that each element of G can be written uniquely in one of the following three forms:

- t^i,
- $(a^{\eta_0})^{t^{\alpha_0}} (a^{\eta_1})^{t^{\alpha_1}} \dots (a^{\eta_k})^{t^{\alpha_k}} t^i$,
- $(a^{-\eta_0})^{t^{\alpha_0}} (a^{-\eta_1})^{t^{\alpha_1}} \dots (a^{-\eta_k})^{t^{\alpha_k}} t^i$,

where $i, k \in \mathbb{Z}$, $k \geq 0$, $0 < \eta_j < p$, $\alpha_0 > \alpha_1 > \cdots > \alpha_k$, and $x^y = y^{-1}xy$.

For example, for $p = 2$,

$$\begin{pmatrix} 8 & \frac{11}{4} \\ 0 & 1 \end{pmatrix}$$

can be written as

$$\begin{pmatrix} 1 & \frac{1}{2^2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{1}{2^1} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 2^1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 2^3 & 0 \\ 0 & 1 \end{pmatrix} = a^{t^2} a^{t^1} a^{t^{-1}} t^3.$$

Define the *level* of a letter in a word $w \in X^*$ to be the t-exponent sum of the prefix of w ending with this letter. For example, the levels of the a letters in the word $a^{t^2} a^t a^{t^{-1}} t^3$ are $-2, -1, 1$ respectively.

If $w \in X^*$, let texp denote the t-exponent sum of w, $l_{\min}$ the minimum level of any letter in w, and $l_{\max}$ the maximum level of a letter in w.

Lemma 36. *If $w \in X^*$ is written on an input tape, then we can compute and store* $\text{texp}, l_{\min}$ *and* $l_{\max}$ *in logspace.*

Proof. We perform the following logspace algorithm:

```
(1) set binary counters $\text{texp}, l_{\min}, l_{\max}$ to zero
(2) scan the input from left to right
      • if the next letter is $t$, increment texp by 1, and set
        $l_{\max} = \max\{\text{texp}, l_{\max}\}$
      • if the next letter is $t^{-1}$, decrement texp by 1, and set
        $l_{\min} = \min\{\text{texp}, l_{\min}\}$
      • if the next letter is $a^{\pm 1}$, do nothing.
```

When the end of the input is reached, the counters $\text{texp}, l_{\min}, l_{\max}$ contain the required values for w, and have absolute value no more than the length of the input. □

We will use the fact that since G is metabelian, words of zero t-exponent sum commute in G. For example, if $u = atatatat^{-2}at^{-2}at$, the subword $tatat^{-2}$ has zero t-exponent sum, and so we may commute it past the first a at level 1 to obtain $at(tatat^{-2})aat^{-2}at$, as illustrated in Figure 1. This means we may collect together $a^{\pm 1}$ letters at the same level without changing the group element represented by a word.

Let $S \subset X^*$ be the set of words of zero t-exponent sum. We define a function $f_S : S \to S$ such that $f_S(u)$ is a word of the form λ or

$$(a^{\eta_0})^{t^{\alpha_0}} (a^{\eta_1})^{t^{\alpha_1}} \dots (a^{\eta_{k-1}})^{t^{\alpha_{k-1}}} (a^{\beta})^{t^{\alpha_k}},$$

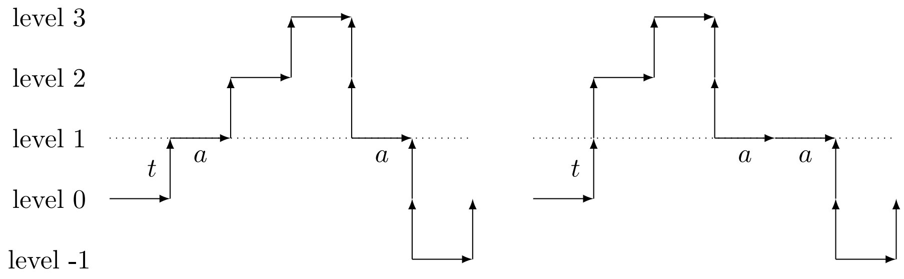

FIGURE 1. Subwords of zero t-exponent commute with a letters.

where $\alpha_0 > \alpha_1 > \cdots > \alpha_k$, $0 < \eta_i < p$, $k \geq 0$, and $\beta \in \mathbb{Z}, \beta \neq 0$, such that u and $f_S(u)$ represent the same element in $\mathrm{BS}(1,p)$. Note that the level of each $a^{\pm 1}$ in the subword $(a^{\eta_i})^{t^{\alpha_i}}$ is $-\alpha_i$. Note also that since β is allowed to range through all integers, the output here is not guaranteed to produce a unique representative for each group element, so we do not claim f_S is a normal form function. Instead, we call $f_S(u)$ an *approximation* of the normal form for u. It is computed using the following algorithm.

Algorithm 37 (Approximation Algorithm)**.** *On input $u \in S$:*

```
(1) run the algorithm in Lemma 36 and store $l_{\min}$ and $l_{\max}$ in binary.
(2) set $l = l_{\min}$, aexp $= 0$ and $\beta = 0$.
(3) while $l \leq l_{\max}$:
    (a) set texp $= 0$
    (b) for each letter $x$ of input, starting at the left most letter:
        • if $x = t$, put texp $=$ texp $+ 1$
        • if $x = t^{-1}$, put texp $=$ texp $- 1$
        • if $x = a$ and texp $= l$, put aexp $=$ aexp $+ 1$
        • if $x = a^{-1}$ and texp $= l$, put aexp $=$ aexp $- 1$
    (c) if $l < l_{\max}$:
        • compute and store (in binary) $q, r \in \mathbb{Z}$
          where aexp $= pq + r$ and $0 \leq r < p$
        • if $r \neq 0$ write $(a^r)^{t^{-l}}$ to the output tape, and set $\beta = r$
        • set aexp $= q$
        else:
        • if aexp $\neq 0$:
            – set $\beta =$ aexp
            – write $(a^{\beta})^{t^{-l_{\max}}}$ to the output tape
        • set aexp $= 0$
        • increment $l$ by 1.
    (d) loop invariant: if $v$ is word written on the output tape then we claim
        that
```

$$\overline{u} = \overline{v(a^{\mathrm{aexp}})^{t^{-l}}[u]_l},$$

where $[u]_l$ is the word obtained from u by ignoring all those occurrences of a and a^{-1} at levels less than l.

Notice that we are effectively computing the p–ary expansion of the upper-right entry in our matrix representation, and that to do so requires that "carrying" a-exponent sums from one level to the next; this is the job of the variable aexp in the algorithm.

Note also that the variable β is changed in step 3(c) only if the new value is nonzero and some $a^{\pm 1}$ letters are written to the output tape. So at the end of the algorithm $\beta = 0$ if and only if the output word has no $a^{\pm 1}$ letters, and the algorithm has no output. If $\beta \neq 0$ then the suffix of the output word is $(a^{\beta})^{t^{-l}}$.

The next three lemmas show that Algorithm 37 computes the function f_S as required, and in logspace.

Lemma 38. *Let u be a word in X^* with t-exponent sum equal to zero. Let m be the minimum level of any a or a^{-1} in u. Let e be the exponent sum of those as in u which are at level m. Then $\overline{u} = \overline{(a^e)^{t^{-m}}[u]_{m+1}}$.*

Proof. Let $a_1, a_2, \ldots, a_s$ be the $a^{\pm 1}$ letters in u that are at level m. Write u as $u_0 a_1 u_1 a_2 u_2 \ldots a_s u_s$ where all $a^{\pm 1}$ letters in u_i are above level m, so $u_0 u_1 \ldots u_s = [u]_{m+1}$. Then the t-exponent sum of u_0 is m, the t-exponent sum of u_i for $1 \leq i < s$ is zero, and for u_s is $-m$. Inserting $t^{-m}t^m$ pairs before and after each a_i we obtain a word

$$v = u_0 t^{-m}(t^m a_1 t^{-m}) t^m u_1 t^{-m}(t^m a_2 t^{-m}) t^m u_2 \ldots t^{-m}(t^m a_s t^{-m}) t^m u_s$$

with $\overline{u} = \overline{v}$. Put $v_0 = u_0 t^{-m}, v_i = t^m u_i t^{-m}$ for $1 \leq i < s$ and $v_s = t^m u_s$, so each v_i has zero t-exponent sum, and $v = v_0 t^m a_1 t^{-m} v_1 t^m a_2 t^{-m} v_2 \ldots t^m a_s t^{-m} v_s$. Then

$$\overline{v} = \overline{t^m a_1 a_2 \ldots a_s t^{-m} v_0 v_1 \ldots v_s}$$

since words of zero t-exponent sum commute, where $\overline{a_1 a_2 \ldots a_s} = \overline{a^e}$. Finally note that $v_0 v_1 \ldots v_s = u_0 t^{-m} t^m u_i t^{-m} \ldots t^m u_{s-1} t^{-m} t^m u_s$ which after cancellation of $t^{-m}t^m$ pairs is $[u]_{m+1}$. $\square$

Lemma 39. *The approximation algorithm is correct.*

Proof. It is clear that the format of the output word is correct, so it remains to show that the output word is equal in the group to the input word. We will first show that the loop invariant defined in step 3d is preserved under one iteration of the main loop. Let l, aexp and v represent the values of these variables at the start of an iteration, that is, at the top of the loop, where v is the word currently written on the output tape. Assume the loop invariant holds, so $\overline{u} = \overline{v(a^{\text{aexp}})^{t^{-l}}[u]_l}$.

Let l', aexp$'$ and v' represent the values of these variables at the end of that iteration, that is, at the point of the loop which is marked with the loop invariant. Note that $l' = l + 1$.

Let e be the exponent sum of those $a^{\pm 1}$s at level l, the lowest level of any $a^{\pm 1}$ letters in $[u]_l$. The algorithm sets aexp$' = q$ where aexp $+ e = pq + r$ and writes $(a^r)^{t^{-l}}$ to the output tape if $r > 0$. So $\overline{v'} = \overline{v(a^r)^{t^{-l}}}$ (which includes the case $r = 0$).

By Lemma 38 we have $\overline{[u]_l} = \overline{(a^e)^{t^{-l}}[u]_{l'}}$. Then

$$\begin{aligned}
\overline{u} &= \overline{v(a^{\text{aexp}})^{t^{-l}}[u]_l} &&= \overline{v(a^{\text{aexp}})^{t^{-l}}(a^e)^{t^{-l}}[u]_{l'}} \\
&= \overline{v(a^{\text{aexp}+e})^{t^{-l}}[u]_{l'}} &&= \overline{v(a^{pq+r})^{t^{-l}}[u]_{l'}} \\
&= \overline{v(a^{r})^{t^{-l}}(a^{pq})^{t^{-l}}[u]_{l'}} &&= \overline{v'(a^{pq})^{t^{-l}}[u]_{l'}} \\
&= \overline{v't^l(a^{pq})t^{-l}[u]_{l'}} &&= \overline{v't^l(ta^qt^{-1})t^{-l}[u]_{l'}} \\
&= \overline{v't^{l+1}(a^{q})t^{-l-1}[u]_{l'}} &&= \overline{v't^{l'}(a^{q})t^{-l'}[u]_{l'}} \\
&= \overline{v'(a^{q})^{t^{-l'}}[u]_{l'}} &&= \overline{v'(a^{\text{aexp}'})^{t^{-l'}}[u]_{l'}}.
\end{aligned}$$

Thus we see that the invariant is preserved.

At the start of the main loop, the loop invariant holds, since $v = \lambda$, aexp $= 0$, $l = l_{\min}$, and $u = [u]_{l_{\min}}$. After the last iteration we have $l = l_{\max}+1$, $[u]_{l_{\max}+1} = \lambda$ and aexp $= 0$, so

$$\overline{u} = \overline{v(a^{\text{aexp}})^{t^{-l}}[u]_l} = \overline{v(a^0)^{t^{-l}}\lambda} = \overline{v},$$

so the word written to the output tape is equal in the group to the input word. □

Lemma 40. *The function f_S can be computed in logspace.*

Proof. At all times the integers aexp, $|q|$ and $|r|$ are at most the length of the input word, so can be computed and stored in binary in logpsace, and each time the main loop is executed the stored values can be overwritten. It follows that the algorithm described runs in logspace. □

For $u \in S$ define β_u to be the value of the variable β stored at the end of the algorithm computing $f_S(u)$.

Corollary 41. *If $u \in S$ and $\beta_u < 0$, then $f_S(u^{-1})$ contains only a letters.*

Proof. If $\beta_u < 0$ then the top right entry of the matrix representing u is negative, so the top right entry of the matrix representing u^{-1} is positive, so $\beta_{u^{-1}}$ is positive, so all $a^{\pm 1}$ letters output by Algorithm 37 have positive exponent. □

Proposition 42. *The normal form*

- t^i,
- $(a^{\eta_0})^{t^{\alpha_0}}(a^{\eta_1})^{t^{\alpha_1}}\dots(a^{\eta_k})^{t^{\alpha_k}}t^i$,
- $(a^{-\eta_0})^{t^{\alpha_0}}(a^{-\eta_1})^{t^{\alpha_1}}\dots(a^{-\eta_k})^{t^{\alpha_k}}t^i$,

where $i, k \in \mathbb{Z}$, $k \geq 0$, $0 < \eta_j < p$, $\alpha_0 > \alpha_1 > \dots > \alpha_k$, and $x^y = y^{-1}xy$, can be computed in logspace.

Proof. Define a function h_S on (nontrivial) words of the form

$$u = (a^{\eta_0})^{t^{\alpha_0}}(a^{\eta_1})^{t^{\alpha_1}}\dots(a^{\eta_{s-1}})^{t^{\alpha_{s-1}}}(a^{\beta})^{t^{\alpha_s}}$$

with $\beta > 0, \alpha_0 < \dots < \alpha_{s-1}, 0 < \eta_i < p$ as follows. Put

$$v = (a^{\eta_0})^{t^{\alpha_0}}(a^{\eta_1})^{t^{\alpha_1}}\dots(a^{\eta_{s-1}})^{t^{\alpha_{s-1}}},$$

so $u = v(a^{\beta})^{t^{\alpha_s}}$. Write $\beta = b_0 + b_1p + \dots + b_\kappa p^\kappa$ with $0 \leq b_i < p$ and $b_\kappa > 0$. Then

$$h_S(u) = v(a^{b_0})^{t^{\alpha_s}}(a^{b_1})^{t^{\alpha_s - 1}}\dots(a^{b_\kappa})^{t^{\alpha_s - \kappa}}.$$

Since
$$\overline{a^\beta} = \overline{(a^{b_0})(a^{b_1})^{t^{-1}} \dots (a^{b_\kappa})^{t^{-\kappa}}}$$
it follows that $\overline{u} = \overline{h_S(u)}$. The following algorithm shows that $h_S(u)$ can be computed in logspace. On input $u = v(a^\beta)^{t^{\alpha_s}}$:

```
(1) output $v$
(2) store $b = \beta$ and $c = \alpha_s$ in binary
(3) while $b > p$:
      • compute $q, r$ so that $0 \leq r < p$ and $b = pq + r$
      • if $r > 0$, output $(a^r)^{t^c}$
      • set $c = c - 1$ and $b = q$
(4) output $(a^b)^{t^c}$.
```

Let $\iota : S \to S$ be the logspace function that computes the inverse of a word given in the proof of Lemma 30. Define $\tau : t \mapsto t, t^{-1} \mapsto t^{-1}, a \mapsto a^{-1}$, which is computable with no memory.

We can compute the normal form as follows. Let $w \in X^*$ be a word written on an input tape. Run the algorithm in Lemma 36 to compute texp and store it in binary. Run the approximation algorithm on $u = wt^{-\text{texp}}$, suppressing output.

```
(1) if $\beta_u = 0$, output $t^{\text{texp}}$.
(2) if $\beta_u > 0$, output $h_S(f_S(u))$, then output $t^{\text{texp}}$.
(3) if $\beta_u < 0$, output $\tau(h_S(f_S(\iota(u))))$, then output $t^{\text{texp}}$.
```

□

Note that by Proposition 12, the length of a logspace normal form for an input word of length n is at most a polynomial in n. In this case, for $p = 2$, the input word $t^{k+1}at^{-k-1}a^{-1}$ of length $2k+4$, has normal form $aa^t a^{t^2} a^{t^3} a^{t^4} \dots a^{t^k}$ of length $1 + k + \sum_{i=1}^{k} 2i = k + k(k+1) = k^2 + 2k + 1$.

9. Logspace embeddable groups

We define a group to be *logspace embeddable* if it embeds in a group which has a logspace normal form.

Our results from the previous sections give us:

Corollary 43. *Being logspace embeddable is closed under direct product, wreath product, and passing to finite index subgroups and supergroups.*

Magnus proved in [8] that a free solvable group can be embedded in an iterated wreath product of $\mathbb{Z}$. (For a modern exposition of this result, see, for example, [11].) Thus we obtain the following corollary of Theorem 22.

Corollary 44. *All finitely generated free solvable groups are logspace embeddable. In particular, all finitely generated free metabelian groups are logspace embeddable.*

Corollary 45. *If G is logspace embeddable, then the word and co-word problems for G are decidable in logspace (and polynomial time).*

Proof. By Lemma 8 we can decide if two words in a group with logspace normal form are equal or not, and moreover by Lemma 9 the algorithm runs is polynomial time. Since the word and coword problems pass to subgroups the result follows. □

While logspace embeddable groups have efficiently decidable word problem, the same cannot be said for their conjugacy or generalised word problems.

Proposition 46. *The generalized word problem and the conjugacy problem are not decidable for logspace embeddable groups.*

Proof. By [10] finitely generated subgroups of the direct product of two finitely generated free groups can have unsolvable membership problem and unsolvable conjugacy problem. □

We are not able to say whether the class of logspace embeddable groups is *strictly* larger than the class of groups having logspace normal forms. If we were able to prove that logspace normal form implies solvable conjugacy problem, for example, then the proposition above would settle this.

Further, we know that all linear groups have logspace word problem by [5], but we are not able to prove that they all have logspace normal forms.

10. Nilpotent groups

In this section we prove that the group of unitriangular $r \times r$ matrices over $\mathbb{Z}$ has logspace normal form, and obtain as a corollary that all finitely generated nilpotent groups are logspace embeddable. It is important to remember that for our purposes, r is a constant, and in this respect our algorithms are not uniform.

Let $r \geq 2$, and let $\mathrm{UT}_r\mathbb{Z}$ be the group of upper triangular matrices over $\mathbb{Z}$ with 1's on the diagonal. For $1 \leq i < j \leq r$, let $E_{i,j}$ denote the elementary matrix obtained from the identity matrix by putting a 1 in position (i, j) and let X be the set of all such elementary matrices and their inverses. $\mathrm{UT}_r\mathbb{Z}$ is generated as a group by X, and we denote by $\overline{w}$ the image of w under the natural homomorphism from the free group on X to $\mathrm{UT}_r\mathbb{Z}$.

Lemma 47. *If w is a word of length n over X, and if a is an entry in the ith super-diagonal of the matrix $\overline{w}$, then $|a| \leq n^i$.*

Proof. We proceed by induction on r. When $r = 2$,

$$E_{1,2} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$$

and $\mathrm{UT}_2\mathbb{Z} \cong \mathbb{Z}$. It is clear that the entry in the off-diagonal of the matrix $\overline{w}$ has absolute value at most n in this case, so the result holds.

Now let $r \geq 3$ and assume the result holds for $r - 1$.

Consider the homomorphism from $\mathrm{UT}_r\mathbb{Z}$ to $\mathrm{UT}_{r-1}\mathbb{Z}$ that takes an $r \times r$ matrix to the $(r-1) \times (r-1)$ matrix in the upper left-hand corner. The kernel of this homomorphism is isomorphic to $\mathbb{Z}^{r-1}$, and $\mathrm{UT}_r\mathbb{Z}$ is the split extension of $\mathrm{UT}_{r-1}\mathbb{Z}$ and this kernel, so with a slight abuse of notation we can consider $\mathrm{UT}_{r-1}\mathbb{Z}$ as a subgroup of $\mathrm{UT}_r\mathbb{Z}$. Furthermore, our chosen generating set is the disjoint union of generators of the form $E_{i,j}^{\pm 1}$ for $j < r$, and $E_{i,r}^{\pm 1}$, which generate $\mathrm{UT}_{r-1}\mathbb{Z}$ and $\mathbb{Z}^{r-1}$ respectively. We will denote by X_r the generating set for $\mathrm{UT}_r\mathbb{Z}$.

Let w be a word in $(X_r)^*$ of length n. We now proceed by induction on n. If $n = 1$, the result is clear, since every entry a in the matrix $\overline{w}$ satisfies $|a| \leq 1$. When $n \geq 2$, we may assume that the lemma holds for $n - 1$.

Let w' be a word of length $n - 1$ over X_r and let x be an element of X_r such that $w = w'x$. Then $\overline{w'}$ is of the form

$$\begin{bmatrix} A & u \\ 0 & 1 \end{bmatrix},$$

where A is an element of $\mathrm{UT}_{r-1}\mathbb{Z}$ and u is a column vector in $\mathbb{Z}^{r-1}$.

There are two cases for the generator x: either $x = E_{i,j}^{\pm 1}$ with $i < j < r$, that is,

$$\begin{bmatrix} B & 0 \\ 0 & 1 \end{bmatrix},$$

where B is of the form $E_{i,j}^{\pm 1} \in X_{r-1}$; or $x = E_{i,r}^{\pm 1}$, that is,

$$\begin{bmatrix} I & v \\ 0 & 1 \end{bmatrix},$$

where I is the identity matrix and v is a column vector of length $r-1$ with one entry ± 1 and the rest 0.

In the first case,

$$\overline{w'x} = \begin{bmatrix} A & u \\ 0 & 1 \end{bmatrix} \begin{bmatrix} B & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} AB & u \\ 0 & 1 \end{bmatrix}.$$

The matrix AB is the product of n generators over X_{r-1}, so by inductive assumption on r the entries in the ith super-diagonals have absolute value at most n^i, and the entries in the last column

$$\begin{bmatrix} u_{r-1} \\ u_{r-2} \\ \vdots \\ u_1 \\ 1 \end{bmatrix}$$

satisfy $u_i \leq (n-1)^i < n^i$ since they come from $\overline{w'}$.

In the second case,

$$\overline{w'x} = \begin{bmatrix} A & u \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I & v \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} A & Av+u \\ 0 & 1 \end{bmatrix}.$$

The entries in the upper left-hand corner satisfy the lemma since they come from w'. Let a be an element of the kth superdiagonal of $\overline{w}$, and suppose as well that a is in the last column of $\overline{w}$. What remains is to show that $|a| < n^k$ in this special case.

The column vector Av is either one of the columns of A, or a column of A multiplied by -1. Suppose that Av is the j'th column of A, or its negation, and denote the entries of Av as follows:

$$\begin{bmatrix} a_{j-1} \\ a_{j-2} \\ \vdots \\ a_1 \\ 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

Denote the entries of u as follows:

$$\begin{bmatrix} u_{r-1} \\ u_{r-2} \\ \vdots \\ u_1 \end{bmatrix}.$$

Note that a_i and u_i are on the i'th super diagonal of $\overline{w'}$, so by our inductive assumption on n, $|a_i|, |u_i| \leq (n-1)^i$. Note also that $j \leq r-1$.

There are three cases to consider. For the first case, let us suppose that $k < r-j$. In this case $a = u_k + 0 = u_k$ and hence $|a| \leq (n-1)^k < n^k$. For the second case, let us suppose that $k = r-j$. In this case, $a = u_k + 1$, and hence $|a| \leq (n-1)^k + 1 \leq n^k$. In the remaining case, $k > r-j$. In this case $a = u_k + a_m$, where $m = k - (r-j)$. Therefore $|a| \leq (n-1)^k + (n-1)^{k-(r-j)}$. Since $j \leq r-1$, $r-j \geq 1$ and

$$|a| \leq (n-1)^k + (n-1)^{k-1} = (n-1)^{k-1}(n-1+1) = n(n-1)^{k-1} < n^k.$$

□

By listing those elementary matrices with a 1 on the first superdiagonal first, followed by those elementary matrices with a 1 on the second superdiagonal next, and so on, we obtain the sequence

$$E_{1,2}, E_{2,3}, \ldots, E_{r-1,r}, E_{1,3}, E_{2,4}, \ldots, E_{r-2,r}, \ \ldots, E_{1,r},$$

which is a polycyclic generating sequence for G and hence gives us a normal form g_X for G.

Theorem 48. *The normal form $g_X(w)$ can be computed in logspace.*

Proof. We begin by describing our algorithm for computing $g_X(w)$. Compute and store the matrix $\overline{w}$. If the entries on the first super-diagonal are $\alpha_1, \alpha_2, \ldots, \alpha_{r-1}$, then $g_X(w)$ starts with the word

$$E_{1,2}^{\alpha_1} E_{2,3}^{\alpha_2} \ldots E_{r-1,r}^{\alpha_{r-1}},$$

so we write this word to the output tape. Next compute the matrix for

$$w_1 = E_{r-1,r}^{-\alpha_{r-1}} \ldots E_{2,3}^{-\alpha_2} E_{1,2}^{-\alpha_1} w.$$

The matrix $\overline{w_1}$ will have 0's along the first super-diagonal. Let $\beta_1, \beta_2, \ldots, \beta_{r-2}$ be the entries on the second super-diagonal of $\overline{w_1}$. The next part of $g_x(w)$ starts with the word

$$E_{1,3}^{\beta_1} E_{2,4}^{\beta_2} \ldots E_{r-2,r}^{\beta_{r-2}},$$

so we write this word to the output tape. Next compute the matrix for

$$w_2 = E_{r-2,r}^{-\beta_{r-2}} \ldots E_{2,4}^{-\beta_2} E_{1,3}^{-\beta_1} w_1.$$

The matrix $\overline{w_2}$ has 0's along the first two super-diagonals. Continue in this way, peeling off the super-diagonals one at a time, obtaining at each stage a word w_i such that $\overline{w_i}$ has 0's along the first i super-diagonals, and writing the part of the normal form $g_X(w)$ that corresponds to the ith super-diagonal as you go.

To show that $g_X(w)$ can be calculated in logspace, it suffices to show that there exist constants D and k such that for all $1 \leq i \leq r-1$, the length of w_i is bounded by Dn^k, since then by Lemma 47, there exists a constant C such that the matrix $\overline{w_i}$ can be stored in space $r^2 \log(C(Dn^k)^{r-1})$, which is $O(\log n)$. We will define D_i and k_i inductively in such a way that for all i, the length of w_i is bounded by $D_i n^{k_i}$

and D_i and k_i are constants in the sense that they do not depend on n. When $i = 0$, $w_i = w$ and we can take $D_0 = 1$ and $k_0 = 1$. Now suppose that D_i and k_i are suitable constants for w_i. Let $\beta_1, \beta_2, \ldots, \beta_p$ be the entries on the $(i+1)$-st super-diagonal of $\overline{w_i}$. By Lemma 47, each β_j is bounded in magnitude by $C(D_i n^{k_i})^{r-1}$. Therefore, the length of w_{i+1} is bounded by $pC(D_i n^{k_i})^{r-1} + D_i n^{k_i}$, which is itself bounded by $rD_i^r(C+1)n^{k_i r}$. We let $D_{i+1} = rD_i^r(C+1)$ and $k_{i+1} = k_i r$. Notice that neither D_i nor k_i depends on n, so from our point of view they are constants. Thus, $D = D_{r-1}$ and $k = k_{r-1}$ are constants such that for all $1 \leq i \leq r-1$, the length of w_i is bounded b Dn^k. □

Corollary 49. *All finitely generated nilpotent groups are logspace embeddable.*

Proof. Let G be a finitely generated nilpotent group. Then G has a finite index subgroup N which is torsion-free ([4], Theorem 3.21). There exists a positive integer r such that N embeds in $\mathrm{UT}_r\mathbb{Z}$ ([15], Theorem 2, p. 88). Therefore N is logspace embeddable. Since by Proposition 16 the class of logspace embeddable groups is closed under finite extension, G is logspace embeddable. □

Corollary 50. *All finitely generated groups of polynomial growth are logspace embeddable.*

Proof. By Gromov's theorem [3] if a finitely generated group has polynomial growth then it has a nilpotent finitely generated subgroup of finite index. The result follows from the previous corollary and Corollary 43. □

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