Some word maps that are non-surjective on infinitely many finite simple groups

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Abstract

We provide the first examples of words in the free group of rank 2 which are not proper powers and for which the corresponding word maps are non-surjective on an infinite family of finite non-abelian simple groups.

1 Introduction

The theory of word maps on finite non-abelian simple groups – that is, maps of the form $(x_1, \ldots, x_k) \to w(x_1, \ldots, x_k)$ for some word w in the free group F_k of rank k – has attracted much recent attention. It was shown in [6, 1.6] that for a given nontrivial word w, every element of every sufficiently large finite simple group G can be expressed as a product of $C(w)$ values of w in G, where $C(w)$ depends only on w; and this has been dramatically improved to $C(w) = 2$ in [4, 5, 11]. Improving $C(w)$ to 1 is not possible in general, as is shown by power words x_1^n, which cannot be surjective on any finite group of order non-coprime to n.

Certain words are surjective on all groups – namely, those in cosets of the form $x_1^{e_1} \ldots. x_k^{e_k} F_k'$ where the e_i are integers with $\gcd(e_1, ..., e_k) = 1$ (see [10, 3.1.1]). The word maps for a small number of other words have been shown to be surjective on all finite simple groups. These include the commutator word $[x_1, x_2]$ (the Ore conjecture [7]), the words $x_1^p x_2^p$ (for a prime p) and variants [3, 8]. Other studies have restricted the simple groups under consideration to families such as $\mathrm{PSL}_2(q)$ (see, for example, [1]). Motivating some of this work is a conjecture of Shalev, stated in [1, Conjecture 8.3]: if $w(x_1, x_2)$ is not a proper power of a non-trivial word, then the corresponding word map is surjective on $\mathrm{PSL}_2(q)$ for all sufficiently large q.

Theorem 1 gives a family of words which are counterexamples to Shalev's conjecture. We believe these are the first non-power words to be proved non-surjective on an infinite family of finite simple groups.

Theorem 1. *Let $k \geq 2$ be an integer such that $2k+1$ is prime, and let w be the word $x_1^2[x_1^{-2}, x_2^{-1}]^k$. Let $p \neq 2k+1$ be a prime of inertia degree $m > 1$ in $\mathbb{Q}(\zeta + \zeta^{-1})$, where ζ is a primitive $(2k+1)$-th root of unity, and $\left(\frac{2}{p}\right) = -1$. Then the word map $(x, y) \to w(x, y)$ is non-surjective on $\mathrm{PSL}_2(q)$ for all $q = p^n$ where n is a positive integer not divisible by 2 or by m.*

Corollary 2. *Let $k \geq 2$ be an integer such that $2k + 1$ is prime, and let w be the word $x_1^2[x_1^{-2}, x_2^{-1}]^k$. Let $p \neq 2k + 1$ be an odd prime such that $p^2 \not\equiv 1 \bmod 16$ and $p^2 \not\equiv 1 \bmod (2k+1)$, and let m be the smallest positive integer with $p^{2m} \equiv 1 \bmod (2k+1)$. Then the word map $(x, y) \to w(x, y)$ is non-surjective on $\mathrm{PSL}_2(q)$ for all $q = p^n$ where n is a positive integer not divisible by 2 or by m.*

The corollary will be deduced from Theorem 1 at the end of the paper. Taking $k = 2$ we obtain the following.

Corollary 3. *If $w = x_1^2[x_1^{-2}, x_2^{-1}]^2$, then the word map $(x, y) \to w(x, y)$ is non-surjective on $\mathrm{PSL}_2(p^{2r+1})$ for all non-negative integers r and all odd primes $p \neq 5$ such that $p^2 \not\equiv 1 \bmod 16$ and $p^2 \not\equiv 1 \bmod 5$.*

2 Proof of Theorem 1

Let K be a field and $G = \mathrm{SL}_2(K)$, and let $\chi : G \to K$ be the trace map. A classical result of Fricke and Klein implies for every word $w \in F_2$, the free group of rank 2, there is a unique polynomial $\tau(w) \in \mathbb{Z}[s, t, u]$ such that for all $x, y \in G$, $\chi(w(x, y))$ is equal to $\tau(w)$ evaluated at $s = \chi(x)$, $t = \chi(y)$, $u = \chi(xy)$. We call $\tau(w)$ the *trace* polynomial of w. A proof of this fact, providing a constructive method of computing $\tau(w)$ for a given word w, can be found in [9, 2.2]. The method is based on the following identities for traces of 2×2 matrices A, B of determinant 1:

$$\begin{aligned}
&\mathrm{Tr}(AB) = \mathrm{Tr}(BA)\\
&\mathrm{Tr}(A^{-1}) = \mathrm{Tr}(A)\\
&\mathrm{Tr}(A^2B) = \mathrm{Tr}(A)\mathrm{Tr}(AB) - \mathrm{Tr}(B).
\end{aligned}$$

Lemma 2.1. *For $k \in \mathbb{N}$ and $w \in F_2$,*

$$(-1)^k + \sum_{i=1}^{k} (-1)^{k-i} \tau(w^i) = \prod_{i=1}^{k} (\tau(w) + \zeta^i + \zeta^{-i}),$$

where ζ is a primitive $(2k+1)$-th root of unity.

Proof. We adapt the proof of [9, Proposition 2.6]. Assume first that $w = x_1$. Let $A := \begin{pmatrix} 0 & 1 \\ -1 & s \end{pmatrix}$. By the uniqueness of the trace polynomial,

$\tau(w^i) = \mathrm{Tr}(A^i) = \mathrm{Tr}\begin{pmatrix} y^i & 0 \\ 0 & y^{-i} \end{pmatrix} = y^i + y^{-i}$, where $y + y^{-1} = s$. Hence

$$\begin{aligned}
\textstyle\sum_{i=1}^k (-1)^{k-i}\tau(w^i) + (-1)^k &= \textstyle\sum_{i=1}^k (-1)^{k-i} y^i + \sum_{i=1}^k (-1)^{k-i} y^{-i} + (-1)^k \\
&= y^{-k} \textstyle\sum_{i=0}^{2k} (-1)^i y^i \\
&= y^{-k} \textstyle\prod_{i=1}^{2k} (y + \zeta^i) \\
&= \textstyle\prod_{i=1}^k (y + \zeta^i)(1 + \zeta^{-i} y^{-1}) \\
&= \textstyle\prod_{i=1}^k (s + \zeta^i + \zeta^{-i}).
\end{aligned}$$

Note that for $v, v_1, v_2 \in F_2$,

$$\tau(v(v_1, v_2)) = \tau(v)(\tau(v_1), \tau(v_2), \tau(v_1 v_2)),$$

so the general case is derived from the special case $w = x_1$ by polynomial evaluation at $s = \tau(w)$, i.e., setting $v = x_1^i$, $v_1 = w$, $v_2 = 1$. ■

Lemma 2.2. *Let $k \in \mathbb{N}$. The trace polynomial of $w = x_1^2 [x_1^{-2}, x_2^{-1}]^k$ factors over $\mathbb{Z}[\zeta + \zeta^{-1}]$ as*

$$(s^2 - 2) \prod_{i=1}^k (s^4 - s^3 tu + s^2 t^2 + s^2 u^2 - 4s^2 + 2 + \zeta^i + \zeta^{-i}),$$

where ζ is a primitive $(2k+1)$-th root of unity.

Proof. Let $c = [x_1^{-2}, x_2^{-1}]$. We claim that

$$\tau(x_1^2 c^k) = (\tau(x_1)^2 - 2)(\sum_{i=1}^k (-1)^{k-i} \tau(c^i) + (-1)^k).$$

The result then follows by Lemma 2.1, since $\tau(x_1) = s$ and $\tau(c) = s^4 - s^3 tu + s^2 t^2 + s^2 u^2 - 4s^2 + 2$.

The proof is by induction on k. The claim is easily verified for $k = 1, 2$. For $k > 1$ it is equivalent to $\tau(x_1^2 c^k) = (\tau(x_1)^2 - 2)\tau(c^k) - \tau(x_1^2 c^{k-1})$. Using the rule $\tau(x^2 y) = \tau(x)\tau(xy) - \tau(y)$ for all $x, y \in F_2$ and the fact that $x_1^{-2} x_2^{-1} = x_2^{-1} x_1^{-2} c$, we deduce that

$$\begin{aligned}
\tau(x_1^2 c^k) &= (\tau(x_1)^2 - 1)\tau(c^k) - \tau(x_1)\tau(x_1 x_2 x_1^{-2} x_2^{-1} c^{k-1}) \\
&= (\tau(x_1)^2 - 1)\tau(c^k) - \tau(x_1)\tau(x_1^{-1} c^k) \\
&= (\tau(x_1)^2 - 1)\tau(c^k) - \tau(x_1^{-2} c^k) - \tau(c^k).
\end{aligned}$$

Thus it suffices to prove that $\tau(x_1^{-2} c^k) = \tau(x_1^2 c^{k-1})$. Now $\tau(x_1^{-2} c^k) = \tau(c)\tau(c^{k-1} x_1^{-2}) - \tau(c^{k-2} x_1^{-2})$. By induction, for $k \geq 3$ this is equal to $\tau(c)\tau(x_1^2 c^{k-2}) - \tau(x_1^2 c^{k-3})$, which is equal to $\tau(x_1^2 c^{k-1})$. ■

Proof of Theorem 1

Let $q = p^n$ be as in the hypothesis of the theorem, let $K = \mathbb{F}_q$, and let w be the word $x_1^2 [x_1^{-2}, x_2^{-1}]^k$. The ring of integers of $\mathbb{Q}(\zeta + \zeta^{-1})$ is $\mathbb{Z}[\zeta + \zeta^{-1}]$ (see [12, Proposition 2.16]). Since $2k + 1$ is prime, $\mathbb{Z}[\zeta + \zeta^{-1}] = \mathbb{Z}[\zeta^i + \zeta^{-i}]$ for every $1 \leq i \leq k$. Let $P \trianglelefteq \mathbb{Z}[\zeta^i + \zeta^{-i}]$ be a prime above p. Then $\mathbb{Z}[\zeta^i + \zeta^{-i}]/P = \mathbb{F}_{p^m}$, in particular $\zeta^i + \zeta^{-i}$ is a primitive element of $\mathbb{F}_{p^m}$ for every $1 \leq i \leq k$.

Suppose that some triple $(s, t, u) \in \mathbb{F}_q^3$ is a zero of the trace polynomial $\tau(w)$. By Lemma 2.2, $\tau(w)$ factors as

$$(s^2 - 2) \prod_{i=1}^{k} (s^4 - s^3tu + s^2t^2 + s^2u^2 - 4s^2 + 2 + \zeta^i + \zeta^{-i}),$$

over $\mathbb{F}_{p^m}$, so $(s, t, u) \in \mathbb{F}_q^3 \subseteq \mathbb{F}_{q^m}^3$ must be a zero of one of the factors. Since $s^2 - 2$ is irreducible over $\mathbb{F}_q$, (s, t, u) must be a zero of $s^4 - s^3tu + s^2t^2 + s^2u^2 - 4s^2 + 2 + \zeta^i + \zeta^{-i}$ for some i. This implies that $\zeta^i + \zeta^{-i} \in \mathbb{F}_q$, which is a contradiction. Hence no element of $\mathrm{SL}_2(q)$ of the form $w(x, y)$ can have trace zero. ∎

Proof of Corollary 2

Let $q = p^n$ be as in the hypothesis of the corollary. The hypothesis $p^2 \not\equiv 1 \bmod 16$ is equivalent to $\left(\frac{2}{p}\right) = -1$. By the cyclotomic reciprocity law (see for example [12, Theorem 2.13]), the inertia degree of p in $\mathbb{Q}(\zeta)$ is m or $2m$. In the former case, m must be odd. Thus in both cases the inertia degree of p in $\mathbb{Q}(\zeta + \zeta^{-1})$ is m, since $\mathbb{Q}(\zeta + \zeta^{-1})$ is a subfield of index 2 in $\mathbb{Q}(\zeta)$. Now $p^2 \not\equiv 1 \bmod (2k + 1)$ implies $m > 1$, and the conclusion follows from Theorem 1. ∎

Remark. Our search for non-surjective words was assisted by [2], which lists representatives of minimal length for certain automorphism classes of words in F_2.

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