Subgroups of the upper-triangular matrix group with maximal derived length and a minimal number of generators

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Abstract. The group $U_n(\mathbb{F})$ of all $n \times n$ unipotent upper-triangular matrices over $\mathbb{F}$ has derived length $d := \lceil \log_2(n) \rceil$, equivalently $2^{d-1} < n \leqslant 2^d$. We prove that $U_n(\mathbb{F})$ has a 3-generated subgroup of derived length d, and it has a 2-generated subgroup of derived length d if and only if $\frac{21}{32}2^d < n \leqslant 2^d$.

1. Introduction

Let $\mathbb{F}$ be a field and let $U_n(\mathbb{F})$ (or U_n) denote the group of $n \times n$ upper-triangular matrices over $\mathbb{F}$ with 1's on the main diagonal and 0's below. If $2^{d-1} < n \leqslant 2^d$, then U_n has derived length d and has a subgroup generated by $n-1$ elements which also has derived length d (see [3]). We show in Theorem 2 that U_n has a 3-generated subgroup with derived length d. In Theorem 6 we show that U_n has a 2-generated subgroup of derived length d if and only if $\frac{21}{32}2^d < n \leqslant 2^d$. It follows that the proportion, $\pi(N)$, of $n \leqslant N$ such that U_n has a 2-generated subgroup of maximal derived length satisfies $\frac{11}{21} < \pi(N) \leqslant 1$, $\liminf \pi(N) = \frac{11}{21}$ and $\limsup \pi(N) = \frac{11}{16}$. Theorems 2 and 6 are constructive in the sense that the generating matrices are explicitly given by recursive formulas.

We shall now introduce some notation and state some well-known properties of U_n (see [3]). The kth term of the lower central series for U_n, denoted $\gamma_k(U_n)$, comprises the matrices $(a_{i,j}) \in U_n$ with $a_{i,j} = 0$ if $0 < j - i < k$. Furthermore, the kth term in the derived series for U_n is $U_n^{(k)} = \gamma_{2^k}(U_n)$.

In the sequel we shall assume that $d = \lceil \log_2(n) \rceil$ and consider subgroups G of U_n where $G^{(d-1)}$ is not trivial. Let $1 \leqslant i < j \leqslant n$ and let $X_{i,j} \in U_n$ be the matrix obtained by adding row j of the identity matrix, I, to row i (so its (i,j)th entry is 1). Then

$$[X_{i,j}, X_{k,\ell}] = X_{i,j}^{-1} X_{k,\ell}^{-1} X_{i,j} X_{k,\ell}$$

equals I if $j < k$, and equals $X_{i,\ell}$ if $j = k$. In order to show that U_n has derived length d for all n satisfying $2^{d-1} < n \leqslant 2^d$, it suffices to show that $\langle X_{1,2}, X_{2,3}, \ldots, X_{n-1,n} \rangle$ has derived length d when $n = 2^{d-1} + 1$. The latter can be proved using induction on d based

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on the following reasoning

$$\begin{aligned}X_{1,9} &= [X_{1,5}, X_{5,9}]\\ &= [\,[X_{1,3}, X_{3,5}], [X_{5,7}, X_{7,9}]\,]\\ &= [\,[\,[X_{1,2}, X_{2,3}], [X_{3,4}, X_{4,5}]\,], [\,[X_{5,6}, X_{6,7}], [X_{7,8}, X_{8,9}]\,]\,].\end{aligned}$$

At the heart of this proof is a binary tree with d layers and $2^d - 1$ vertices. The vertices at layer k are the elements $X_{1+(i-1)2^{k-1},1+i2^{k-1}}$ of $U_n^{(k-1)}$. If $j = 1 + (i-1)2^{k-1}$, then the vertices $X_{j,j+2^{k-1}}$ and $X_{j+2^{k-1},j+2^k}$ of layer k are joined to $X_{j,j+2^k}$ on the next layer.

2. 3-generated subgroups

The idea behind the proof of Theorem 2 is to "re-cycle" vertices of the above binary tree. For example, the four matrices $X_{1,2}, X_{2,3}, X_{3,4}, X_{4,5}$ are not needed to show that $X_{1,5} \in U_5^{(2)}$: three matrices suffice as

$$[\,[X_{1,2}, X_{2,3}X_{3,4}], [X_{2,3}X_{3,4}, X_{4,5}]\,] = [X_{1,3}X_{1,4}, X_{3,5}] = X_{1,5}.$$

The graph at the heart of the proof of Theorem 2 has fewer vertices than the complete bipartite binary tree with $2^d - 1$ vertices. It has d layers with 3 vertices per layer, where the vertices of layer k correspond to elements of $G^{(k-1)}$. Let A, B, C be the matrices corresponding to the vertices of layer k. Then the commutators $[B,C]$, $[C,A]$, $[A,B]$ correspond to the vertices of layer $k+1$. Thus the edges between layers k and $k+1$ form a bipartite graph K, and the full graph is obtained by joining $d-1$ copies of K end-to-end. Our objective is to inductively construct three layer 1 matrices, so that at least one of the layer d matrices is non-trivial.

Let F be the free group $\langle x_1, x_2, x_3 \mid \ \rangle$ of rank 3. The following lemma was much harder to conceive than to prove.

Lemma 1. *Let d be a positive integer, and let $n = 2^{d-1} + 1$. Then there exist matrices $A_n, B_n, C_n \in U_n$ and a word $w_n(x_1, x_2, x_3) \in F^{(d-1)}$ such that*

$$(1) \qquad w_n(A_n, B_n, C_n) = X_{1,n},\ \ w_n(B_n, C_n, A_n) = I,\ \ \text{and } w_n(C_n, A_n, B_n) = I.$$

Proof. The proof uses induction on d. When $d = 1$, take $w_2(x_1, x_2, x_3) = x_1$ and $A_2 = X_{1,2}$, $B_2 = C_2 = I$. (More generally, if $r^3 + s^3 + t^3 - 3rst \neq 0$ in $\mathbb{F}$ where $r, s, t \in \mathbb{Z}$, then we may take $w_2 = x_1^r x_2^s x_3^t$ and find $A_2, B_2, C_2 \in U_2$ such that (1) holds.) Suppose that $A_n, B_n, C_n \in U_n$ and $w_n \in F^{(d-1)}$ satisfy (1). We shall construct appropriate $A_{2n-1}, B_{2n-1}, C_{2n-1}$ and w_{2n-1}. Now $n = 2^{d-1} + 1$ and $2n - 1 = 2^d + 1$. There is a surjective homomorphism

$$\pi\colon U_{2n-1} \to U_n \times U_n \quad \text{given by} \quad \pi(A) = (\lambda(A), \rho(A)),$$

where $\lambda(A)$ is the upper-left $n \times n$ submatrix of A, and $\rho(A)$ is the lower-right $n \times n$ submatrix of A. Note that $\lambda(A)$ and $\rho(A)$ overlap at the (n,n)th entry of A, which is a 1.

Choose $A_{2n-1}, B_{2n-1}, C_{2n-1} \in U_{2n-1}$ such that

$$\pi(A_{2n-1}) = (A_n, B_n), \qquad \pi(B_{2n-1}) = (B_n, C_n), \qquad \pi(C_{2n-1}) = (C_n, A_n).$$

Clearly A_{2n-1}, B_{2n-1} and C_{2n-1} are not uniquely defined. (A different choice may be obtained by multiplying by an element of $\ker(\pi) \cong \mathbb{F}^{(n-1)^2}$.) Define w_{2n-1} by

$$w_{2n-1}(x_1, x_2, x_3) = [\, w_n(x_1, x_2, x_3), w_n(x_3, x_1, x_2)\,].$$

Clearly, $w_{2n-1} \in F^{(d)}$.

Consider $w_{2n-1}(A_{2n-1}, B_{2n-1}, C_{2n-1})$. Now

$$\begin{aligned}\pi(\, w_n(A_{2n-1}, B_{2n-1}, C_{2n-1})\,) &= w_n(\pi(A_{2n-1}), \pi(B_{2n-1}), \pi(C_{2n-1}))\\ &= \big(\, w_n(A_n, B_n, C_n),\, w_n(B_n, C_n, A_n)\,\big)\\ &= (X_{1,n}, I).\end{aligned}$$

Similarly,

$$\begin{aligned}\pi(w_n(B_{2n-1}, C_{2n-1}, A_{2n-1})) &= (I, I) \quad \text{and}\\ \pi(w_n(C_{2n-1}, A_{2n-1}, B_{2n-1})) &= (I, X_{1,n}).\end{aligned}$$

Now $\pi(X_{1,n}) = (X_{1,n}, I)$ and $\pi(X_{n,2n-1}) = (I, X_{1,n})$. (Here we can tell from the context whether $X_{1,n}$ lies in U_{2n-1} or U_n.) Therefore

$$\begin{aligned}w_n(A_{2n-1}, B_{2n-1}, C_{2n-1}) &= X_{1,n}Z_1,\\ w_n(B_{2n-1}, C_{2n-1}, A_{2n-1}) &= Z_2, \quad \text{and}\\ w_n(C_{2n-1}, A_{2n-1}, B_{2n-1}) &= X_{n,2n-1}Z_3\end{aligned}$$

where $Z_1, Z_2, Z_3 \in \ker(\pi)$. Since $\ker(\pi)$ is abelian, and is centralized by both $X_{1,n}$ and $X_{n,2n-1}$, it follows that

$$\begin{aligned}w_{2n-1}(A_{2n-1}, B_{2n-1}, C_{2n-1}) &= [X_{1,n}Z_1, X_{n,2n-1}Z_3]\\ &= [X_{1,n}, X_{n,2n-1}] = X_{1,2n-1},\\ w_{2n-1}(B_{2n-1}, C_{2n-1}, A_{2n-1}) &= [Z_2, X_{1,n}Z_1] = I,\\ w_{2n-1}(C_{2n-1}, A_{2n-1}, B_{2n-1}) &= [X_{n,2n-1}Z_3, Z_2] = I.\end{aligned}$$

This completes the induction, and the proof. □

Recall the observation that $U_n(\mathbb{F})$ has derived length $d := \lceil \log_2(n) \rceil$, and the subgroup $\langle X_{1,2}, X_{2,3}, \dots, X_{n-1,n}\rangle$ has $n-1$ generators and derived length d.

Theorem 2. *The group $U_n(\mathbb{F})$ of $n \times n$ upper-triangular matrices over a field $\mathbb{F}$ with all eigenvalues 1, has a 3-generated subgroup whose derived length is $d := \lceil \log_2(n) \rceil$. Furthermore, if $n \leqslant \frac{5}{8}2^d$ then $U_n(\mathbb{F})$ has no 2-generated subgroup of derived length d.*

Proof. Set $m = 2^{d-1}+1$. Then both U_m and U_n have derived length d. By Lemma 1, U_m has a 3-generated subgroup with derived length d, and hence so too does U_n, as U_n has a subgroup isomorphic to U_m.

If $d < 3$, then there are no integers in the range $\frac{1}{2}2^d < n \leqslant \frac{5}{8}2^d$. Suppose $d \geqslant 3$ and $G = \langle A, B\rangle$ is a 2-generated subgroup of U_n where $\frac{1}{2}2^d < n \leqslant \frac{5}{8}2^d$. Then

$$\gamma_2(G)/\gamma_3(G) = \langle [A,B]\gamma_3(G)\rangle$$

is cyclic, and therefore

$$G^{(2)} = [\gamma_2(G), \gamma_2(G)] = [\gamma_2(G), \gamma_3(G)] \subseteq \gamma_5(G).$$

A simple induction shows $G^{(d-1)} \subseteq \gamma_{5\cdot 2^{d-3}}(G)$ for $d \geqslant 3$. Since $n \leqslant 5 \cdot 2^{d-3}$, we have

$$G^{(d-1)} \subseteq \gamma_{5\cdot 2^{d-3}}(G) \subseteq \gamma_n(G) \subseteq \gamma_n(U_n) = \{I\}.$$

Therefore G has derived length less than d. □

In the above proof, there were choices for A_2, B_2, C_2 and for the subsequent generators A_n, B_n, C_n where $n = 2^{d-1}+1$. However, once A_2, B_2 and C_2 were specified, the $(i, i+1)$ entries of A_n, B_n, C_n $(d > 1)$ were determined, but the (i, j) entries with $j - i > 1$ could be arbitrary. It should not surprise the reader that different choices for A_2, B_2 and C_2 can yield different subgroups $\langle A_n, B_n, C_n\rangle$.

We shall give an example of a 2-generated group $G = \langle A, B\rangle$ of U_n that shows that both the derived length and the order can depend on $\mathbb{F}$. Let G be the subgroup $\langle A, B\rangle$ of U_6 where $A = X_{1,2}X_{5,6}$ and $B = X_{2,3}X_{3,4}^{-1}X_{4,5}$, and suppose that $\mathrm{char}(\mathbb{F}) = p$ is prime. It follows from $[\,[\,[B,A],B],[B,A]\,] = X_{1,6}^2$ and $[\,[\,[B,A],A],[B,A]\,] = I$ that G is metabelian if $p = 2$, and has derived length 3 if $p > 2$. Furthermore, $|G| = p^7$ if $p = 2, 3$ and $|G| = p^6$ if $p > 3$. In the latter case G has maximal class (see [1, p. 61]).

3. 2-generated subgroups

Suppose that $\frac{5}{8}2^d < n \leqslant 2^d$. It is natural to ask whether $U_n(\mathbb{F})$ has a 2-generated subgroup of derived length d. If $U_m(\mathbb{F})$ has a 2-generated subgroup of derived length d, then so too does $U_n(\mathbb{F})$ all n satisfying $m \leqslant n \leqslant 2^d$. In this section we show that the smallest value of m for which U_m has a 2-generated subgroup of derived length d is $m = \lfloor \frac{21}{32}2^d \rfloor + 1$. This is clearly the case if $0 \leqslant d < 3$. Henceforth assume that $d \geqslant 3$.

Let $F = \langle a, b \mid \ \rangle$ denote a free group of rank 2. Then $\gamma_r(F)/\gamma_{r+1}(F)$ is an abelian group, for each positive integer r, which is freely generated by the basic commutators of weight k (see [2]). Thus a typical element of $\gamma_2(F)/\gamma_4(F)$ has the form $[b,a]^i[b,a,a]^j[b,a,b]^k\gamma_4(F)$, where $[b,a,a]$ and $[b,a,b]$ denote left-normed commutators, i.e. $[\,[b,a],a]$ and $[\,[b,a],b]$ respectively. We shall need three lemmas in the sequel. Lemmas 3 and 4 are standard so we omit their proofs.

Lemma 3. *Let $x, x' \in \gamma_r(F)$ and $y, y' \in \gamma_s(F)$ where $x \equiv x' \mod \gamma_{r+1}(F)$ and $y \equiv y' \mod \gamma_{s+1}(F)$. Then $[x, y] \equiv [x', y'] \mod \gamma_{r+s+1}(F)$.*

Applying Lemma 3 to $[\,[b,a]^i[b,a,a]^j[b,a,b]^k,\ [b,a]^\ell\,]$ shows that

$$[\,[b,a,a],[b,a]\,]\gamma_6(F) \quad \text{and} \quad [\,[b,a,b],[b,a]\,]\gamma_6(F)$$

generate $F^{(2)}\gamma_6(F)/\gamma_6(F)$.

Lemma 4. *Let $T_{r,n}(\tau_1,\dots,\tau_{n-r})$ denote a coset of $\gamma_{r+1}(U_n)$ comprising matrices $(t_{i,j})$ satisfying $t_{i,j} = 0$ if $1 \leqslant j - i < r$, $t_{i,j} = \tau_i$ if $j - i = r$, and $t_{i,j}$ arbitrary if $j - i > r$. Then $[T_{r,n}(\alpha_1,\dots,\alpha_{n-r}), T_{s,n}(\beta_1,\dots,\beta_{n-s})]$ is contained in*

$$T_{r+s,n}(\alpha_1\beta_{1+r} - \alpha_{1+s}\beta_1, \dots, \alpha_{n-r-s}\beta_{n-s} - \alpha_{n-r}\beta_{n-r-s}).$$

How might we go about finding matrices $A, B \in U_n$ such that $\langle A, B\rangle$ has derived length d? Motivated by the previous section we suspect that the $(i, i+1)$ entries of A and B are important. Let $A \in T_{1,n}(\alpha_1,\dots,\alpha_{n-1})$ and $B \in T_{1,n}(\beta_1,\dots,\beta_{n-1})$ where the α_i and the β_j are regarded as variables. An evaluation homomorphism from the polynomial ring

$$P = \mathbb{Z}[\alpha_1,\dots,\alpha_{n-1},\beta_1,\dots,\beta_{n-1}]$$

to $\mathbb{F}$ gives rise to a group homomorphism $\phi : U_n(P) \to U_n(\mathbb{F})$. We shall find a word $c_{n-1}(a,b) \in \gamma_{n-1}(F) \cap F^{(d-1)}$ and values for the α_i and β_j in $\mathbb{F}$ such that $c_{n-1}(\phi(A), \phi(B))$ equals $X_{1,n}$ or $X_{1,n}^{-1}$.

The first case not excluded by Theorem 2, or already excluded, is $n = 6$. Let $c_5(a,b)$ equal $[\,[b,a,a],[b,a]\,]$. By repeated application of Lemma 4 the $(1,6)$ entry of $c_5(A,B)$ is

$$\begin{aligned}
[c_5(A,B)]_{1,6} &= [\,[B,A,A],[B,A]\,]_{1,6}\\
&= [B,A,A]_{1,4}[B,A]_{4,6} - [B,A]_{1,3}[B,A,A]_{3,6}\\
&= -\alpha_1\alpha_2\beta_3\alpha_4\beta_5 + \alpha_1\alpha_2\beta_3\beta_4\alpha_5 + 3\alpha_1\beta_2\alpha_3\alpha_4\beta_5 - 4\alpha_1\beta_2\alpha_3\beta_4\alpha_5\\
&\quad + \alpha_1\beta_2\beta_3\alpha_4\alpha_5 - 2\beta_1\alpha_2\alpha_3\alpha_4\beta_5 + 3\beta_1\alpha_2\alpha_3\beta_4\alpha_5 - \beta_1\alpha_2\beta_3\alpha_4\alpha_5
\end{aligned}$$

We make some remarks about this polynomial. First each monomial summand has five variables. The variables have distinct subscripts and contain three α's and two β's. The polynomial has integer coefficients and $[B,A,A]$ contributes two α_i and one β_j to the first three variables, or to the last three variables of each monomial summand. Similarly, $[B,A]$ contributes an α_i and a β_j to the first two variables, or to the last two variables of each monomial summand. Thus, even without computing $[c_5(A,B)]_{1,6}$, we know that $\alpha_1\alpha_2\alpha_3\beta_4\beta_5$ is not a summand. Setting $\alpha_1 = \alpha_2 = \beta_3 = \alpha_4 = \beta_5 = 1$ and $\beta_1 = \beta_2 = \alpha_3 = \beta_4 = \alpha_5 = 0$ shows that $[c_5(\phi(A),\phi(B))]_{1,6} = -1$ and hence $c_5(\phi(A),\phi(B)) = X_{1,6}^{-1}$. This proves that $\langle\phi(A),\phi(B)\rangle$ is a 2-generated subgroup of $U_6(\mathbb{F})$ of derived length 3 for all fields $\mathbb{F}$.

Many of the above remarks generalize *mutatis mutandis* to other words in the subgroup $\gamma_{n-1}(F) \cap F^{(d-1)}$. We shall use the following lemma repeatedly.

Lemma 5. (Multiplication Lemma) *With the above notation, suppose that $w \in \gamma_r(F)$, $w' \in \gamma_s(F)$, and $[w(A,B)]_{1,1+r}$ and $[w'(A,B)]_{1,1+s}$ have monomial summands m and m' respectively. If $r \geqslant s$, and no monomial summand of $[w'(A,B)]_{1,1+s}$ divides m, then $m\psi_r(m')$ is a monomial summand of $[\,[w(A,B), w'(A,B)]\,]_{1,1+r+s}$ where $\psi_r(m')$ is the polynomial obtained from m' by adding r to each subscript.*

Proof. By Lemma 4, $[\,[w(A,B), w'(A,B)]\,]_{1,1+r+s}$ equals

$$[w(A,B)]_{1,1+r}[w'(A,B)]_{1+r,1+r+s} - [w'(A,B)]_{1,1+s}[w(A,B)]_{1+s,1+s+r}$$

and $m\psi_r(m')$ divides the first term. However, as no monomial summand of $[w'(A,B)]_{1,1+s}$ divides m, it follows that $m\psi_r(m')$ is a monomial summand of $[\,[w(A,B), w'(A,B)]\,]_{1,1+r+s}$ as desired. □ □

By Theorem 2, the next case of interest is when $n = 11$. Mimicking the $n = 6$ case, we seek a word $c_{10}(a,b) \in \gamma_{10}(F) \cap F^{(3)}$ such that the polynomial $[c_{10}(A,B)]_{1,11}$ has a monomial summand with coefficient ± 1. We then assign the value of 1 to the variables in this summand, and zero to the variables not in the summand. Since $F^{(2)}\gamma_6(F)/\gamma_6(F)$ has two generators, it follows from Lemma 3 that $F^{(3)}\gamma_{11}(F)/\gamma_{11}(F) = \langle c_{10}(a,b)\gamma_{11}(F)\rangle$ is cyclic where

$$c_{10}(a,b) = [\,[\,[b,a,b],[b,a]\,], c_5(a,b)] = [\,[\,[b,a,b],[b,a]\,],[\,[b,a,a],[b,a]\,]\,].$$

We abbreviate the phrase "m is a monomial summand of p" by "$m \in p$". Now

$$m_5 = \beta_1\beta_2\alpha_3\alpha_4\beta_5 \in [\,[\,[B,A,B],[B,A]\,]\,]_{1,6} \quad \text{and}$$
$$m_5' = \alpha_1\alpha_2\beta_3\beta_4\alpha_5 \in [c_5(A,B)]_{1,6}.$$

Hence by Lemma 5

$$m_{10} = m_5\psi_5(m_5') = \beta_1\beta_2\alpha_3\alpha_4\beta_5\alpha_6\alpha_7\beta_8\beta_9\alpha_{10} \in [c_{10}(A,B)]_{1,11}.$$

Setting $\beta_1 = \beta_2 = \alpha_3 = \cdots = \alpha_{10} = 1$ and $\alpha_1 = \alpha_2 = \beta_3 = \cdots = \beta_{10} = 0$ shows that U_{11} has a 2-generated subgroup of derived length 4.

Theorem 6. *Let $d = \lceil \log_2(n) \rceil$. Then U_n has a 2-generated subgroup of derived length d if and only if $\frac{21}{32}2^d < n \leqslant 2^d$.*

Proof. Suppose that U_n has a 2-generated subgroup G of derived length d. It follows from Theorem 2 that $\frac{5}{8}2^d < n \leqslant 2^d$. However, if $0 \leqslant d < 5$ then $\lfloor \frac{5}{8}2^d \rfloor = \lfloor \frac{21}{32}2^d \rfloor$. Hence $\frac{21}{32}2^d < n \leqslant 2^d$ for $d < 5$. Suppose now that $d \geqslant 5$. We showed in the preamble to this theorem that $F^{(3)}\gamma_{11}(F)/\gamma_{11}(F)$ is cyclic. Hence by Lemma 3, $F^{(4)} \subseteq \gamma_{21}(F)$. For $d \geqslant 5$, a simple induction shows that $F^{(d-1)} \subseteq \gamma_{21\cdot 2^{d-5}}(F)$. Since $G^{(d-1)} \subseteq \gamma_{21\cdot 2^{d-5}}(G)$ and $\gamma_n(G) = \{I\}$ it follows that $21 \cdot 2^{d-5} < n \leqslant 2^d$ as desired.

Conversely, suppose $\frac{21}{32}2^d < n \leqslant 2^d$. If $d = 0,1,2,3,4$, then the values of $n = \lfloor \frac{21}{32}2^d \rfloor + 1$ are $1,2,3,6,11$ respectively. In each of these cases we have shown that U_n has a 2-generated subgroup of derived length d. Suppose henceforth that $d \geqslant 5$. We shall give a recursive procedure for constructing a 2-generated subgroup of U_n. It suffices to do this for $n = 21 \cdot 2^{d-5} + 1$.

We use induction on d. The initial case when $d = 5$ and $n = 22$ requires the most lengthy calculations. Note that the hypothesis in Lemma 5 that no monomial summand of $[w'(A,B)]_{1,1+s}$ divides m is easily verified in the case when the first s variables of m have a different number of α's than one (and hence every) summand of $[w'(A,B)]_{1,1+s}$. A lengthy argument which repeatedly uses this observation and the Multiplication Lemma shows that

$$\begin{aligned} m_{21} &= -\alpha_1\alpha_2\alpha_3\beta_4\beta_5\alpha_6\psi_6(m_5)\psi_{11}(m_{10}) \in c_{21}(a,b)\\ m'_{21} &= \quad\alpha_1\alpha_2\beta_3\beta_4\beta_5\alpha_6\psi_6(m_5)\psi_{11}(m_{10}) \in c'_{21}(a,b)\\ m''_{21} &= -\beta_1\beta_2\beta_3\alpha_4\alpha_5\beta_6\psi_6(m_5)\psi_{11}(m_{10}) \in c''_{21}(a,b) \end{aligned}$$

where

$$\begin{aligned} c_{21}(a,b) &= [\,[\,[\,[\,[b,a,a,a],[b,a]\,],c_5(a,b)],c_{10}(a,b)]\\ c'_{21}(a,b) &= [\,[\,[\,[\,[b,a,a,b],[b,a]\,],c_5(a,b)],c_{10}(a,b)]\\ c''_{21}(a,b) &= [\,[\,[\,[\,[b,a,b,b],[b,a]\,],c_5(a,b)],c_{10}(a,b)]. \end{aligned}$$

This proves the result for $d = 5$ because the polynomial $[c_{21}(A,B)]_{1,22}$ has a monomial summand with coefficient ±1. The number of α's in m_{21}, m''_{21}, m'_{21} is congruent to 0, 1, 2 modulo 3 respectively, and so by the Multiplication Lemma

$$\begin{aligned} m'_{21}\psi_{21}(m''_{21}) &\in d_{21}(a,b) = [c'_{21}(a,b),c''_{21}(a,b)]\\ m''_{21}\psi_{21}(m_{21}) &\in d'_{21}(a,b) = [c''_{21}(a,b),c_{21}(a,b)]\\ m_{21}\psi_{21}(m'_{21}) &\in d''_{21}(a,b) = [c_{21}(a,b),c'_{21}(a,b)]. \end{aligned}$$

The argument may be applied repeatedly as the number of α's occurring in $m'_{21}\psi_{21}(m''_{21})$, $m''_{21}\psi_{21}(m_{21})$, $m_{21}\psi_{21}(m'_{21})$ is congruent to 0, 1, 2 modulo 3 respectively. This completes the inductive proof. □ □

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