ON MODULAR AND CANCELLABLE ELEMENTS OF THE LATTICE OF SEMIGROUP VARIETIES

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Abstract. We completely determine all semigroup varieties satisfying a permutational identity of length 3 that are modular elements of the lattice of all semigroup varieties. Using this result, we provide an example of a semigroup variety that is a modular but not cancellable element of this lattice.

1. Introduction and summary

There are a number of articles devoted to an examination of special elements in the lattice $\text{SEM}$ of all semigroup varieties (see surveys [8, Section 14] and [10]). Here we continue these considerations and examine special elements of two types, namely, modular and cancellable elements. Recall that an element $x$ of a lattice $\langle L; \lor, \land \rangle$ is called

- modular if $$(\forall y, z \in L) \ (y \leq z \rightarrow (x \lor y) \land z = (x \land z) \lor y),$$
- cancellable if $$(\forall y, z \in L) \ (x \lor y = x \lor z \& x \land y = x \land z \rightarrow y = z).$$

It is evident that every cancellable element of a lattice is modular. A valuable information about modular and cancellable elements in abstract lattices can be found in [5], for instance.

Several results about modular elements of the lattice $\text{SEM}$ were provided in the papers [2, 7, 9]. In particular, commutative semigroup varieties that are modular elements in $\text{SEM}$ are completely determined in [9, Theorem 3.1]. Further, it is verified in [1] that the properties of being modular and cancellable elements of $\text{SEM}$ are equivalent in the class of commutative semigroup varieties. The objective of this article is to prove that this equivalence is not the case in slightly wider class, namely in the class of semigroup varieties satisfying a permutational identity of length 3.

A semigroup variety is called a nil-variety if it consists of nilsemigroups. Semigroup words unlike letters are written in bold. Two sides of identities we connect by the symbol $\approx$, while the symbol $=$ stands for the equality relation on the free semigroup. As usual, we write the pair of identities $xu \approx ux \approx u$ where the letter $x$ does not occur in the word $u$ in the short form $u \approx 0$ and

2010 Mathematics Subject Classification. Primary 20M07, secondary 08B15.

Key words and phrases. Semigroup, variety, lattice of varieties, permutational identity, modular element of a lattice, cancellable element of a lattice.

The work was partially supported by the Ministry of Education and Science of the Russian Federation (project 1.6018.2017/8.9) and by the Russian Foundation for Basic Research (grant No. 17-01-00551).
refer to the expression $u \approx 0$ as to a single identity. A permutational identity is an identity of the form
\begin{equation}
 x_1 x_2 \cdots x_n \approx x_{1\pi} x_{2\pi} \cdots x_{n\pi}
 \end{equation}
where $\pi$ is a non-trivial permutation on the set $\{1, 2, \ldots, n\}$. The number $n$ is called a length of the identity (1.1). We denote by $T$ the trivial semigroup variety and by $SL$ the variety of all semilattices.

The main result of this note is the following

**Theorem 1.1.** A semigroup variety $V$ satisfying a permutational identity of length 3 is a modular element in the lattice $SEM$ if and only if $V = M \lor N$ where $M$ is one of the varieties $T$ or $SL$, while the variety $N$ satisfies one of the following identity systems:

\begin{enumerate}
  \item[(1.2)] $xyz \approx zyx, x^2 y \approx 0$;
  \item[(1.3)] $xyz \approx yzx, x^2 y \approx 0$;
  \item[(1.4)] $xyz \approx yxz, xyzt \approx xzt, xy^2 \approx 0$;
  \item[(1.5)] $xyz \approx zxy, xyzt \approx yzt, x^2 y \approx 0$.
\end{enumerate}

We denote by $S_n$ the full permutation group on the set $\{1, 2, \ldots, n\}$. The semigroup variety given by an identity system $\Sigma$ is denoted by $\text{var} \Sigma$. In [1, Question 3.2], the question is asked whether there is a semigroup variety that is a modular but not cancellable element of the lattice $SEM$. The following result gives the affirmative answer to this question.

**Proposition 1.2.** Let $\rho$ be a non-trivial permutation from $S_3$. The variety $\text{var}\{xyzt \approx xyt, x_1 x_2 x_3 \approx x_{1\rho} x_{2\rho} x_{3\rho}\}$ is a modular but not cancellable element of the lattice $SEM$.

The article consists of three sections. Section 2 contains auxiliary results. In Section 3 we verify Theorem 1.1 and Proposition 1.2.

## 2. Preliminaries

We denote by $F$ the free semigroup over a countably infinite alphabet. If $u \in F$ then $\text{con}(u)$ denotes the set of all letters occurring in the word $u$. The following claim is well known and easily verified.

**Lemma 2.1.** An identity $u \approx v$ holds in the variety $SL$ if and only if $\text{con}(u) = \text{con}(v)$. $\square$

An element $x$ of a lattice $\langle L; \lor, \land \rangle$ is called neutral if, for any $y, z \in L$, the sublattice of $L$ generated by $x$, $y$ and $z$ is distributive. It is well known that the variety $SL$ is a neutral element of the lattice $SEM$ [12, Proposition 4.1] and an atom of this lattice (see the survey [8], for instance). This fact together with [6, Corollary 2.1] immediately imply the following

**Lemma 2.2.** For a semigroup variety $V$, the following are equivalent:

\begin{enumerate}
  \item[(i)] the variety $V$ is a modular element of the lattice $SEM$;
  \item[(ii)] the variety $SL \lor V$ is a modular element of the lattice $SEM$;
\end{enumerate}
(iii) the variety SL ∨ V is a modular element of the coideal |SL| of the lattice SEM.

The following claim gives a strong necessary condition for a semigroup variety to be a modular element in the lattice SEM.

**Proposition 2.3.** If V is a modular element of the lattice SEM then either V coincides with the variety of all semigroups or V = M ∨ N where M is one of the varieties T or SL, while N is a nil-variety.

This proposition was proved (in slightly weaker form and in some other terminology) in [2, Proposition 1.6]. It was formulated in the form given here in [9, Proposition 2.1]. A direct and transparent proof of Proposition 2.3 not depending on a technique from [2] is provided in [7].

As we have already mentioned, commutative varieties that are modular elements in SEM are completely classified in [9, Theorem 3.1]. We need the following consequence of this result that was verified in [11], in fact.

**Proposition 2.4.** If a semigroup variety satisfies the identities

\[ x^2y \approx 0 \text{ and } xy \approx yx \]

then it is a modular element in SEM.

We need also the following claim that is a part of [9, Theorem 4.5].

**Lemma 2.5.** Let V be a nil-variety of semigroups satisfying an identity of the form 

\[ x_1x_2x_3 \approx x_1x_2x_3\pi \]

where \( \pi \) is a non-trivial permutation from \( S_3 \). If V is a modular element of the lattice SEM then V satisfies also:

(i) all permutational identities of length 4;
(ii) the identity \( xy^2 \approx 0 \) whenever \( \pi = (12) \);
(iii) the identity \( x^2y \approx 0 \) whenever \( \pi \) is one of the permutations (13), (23) or (123).

For a natural number \( n \) and a semigroup variety \( V \), we denote by \( \text{Perm}_n(V) \) the set of all permutations \( \pi \in S_n \) such that \( V \) satisfies the identity (1.1). Clearly, \( \text{Perm}_n(V) \) is a subgroup in \( S_n \). If \( 1 \leq i \leq n \) then we denote by \( \text{Stab}_i(n) \) the set of all permutations \( \pi \in S_n \) with \( i\pi = i \). Obviously, \( \text{Stab}_i(n) \) also is a subgroup in \( S_n \). Moreover, it is well known that \( \text{Stab}_i(n) \) is a maximal proper subgroup in \( S_n \). We need the following partial cases of results of the article [3].

**Lemma 2.6.** Let V be a nil-variety of semigroups.

1) If \( V \) satisfies a non-trivial identity of the form \( x_1x_2x_3 \approx x_1x_2x_3\pi \) and \( n \geq 4 \) then
   (i) \( \text{Perm}_n(V) \supseteq \text{Stab}_1(n) \) whenever \( \pi = (12) \);
   (ii) \( \text{Perm}_n(V) \supseteq \text{Stab}_1(1) \) whenever \( \pi = (23) \);
   (iii) \( \text{Perm}_n(V) = S_n \) otherwise.

2) If \( V \) satisfies the identity \( xyzt \approx xzty \) and \( n \geq 5 \) then \( \text{Perm}_n(V) \supseteq \text{Stab}_1(1) \).

If \( a \in F \) then we denote by \( \ell(a) \) the length of the word \( a \). The following lemma readily follows from the proof of [4, Lemma 1].
Lemma 2.7. If a nil-variety of semigroups satisfies an identity of the form
\[ x_1 x_2 \cdots x_n \approx w \] where \( \ell(w) \neq n \) then it satisfies also the identity \( x_1 x_2 \cdots x_n \approx 0 \).

If a, b \in F and b may be obtained from a by renaming of letters then we say that the words a and b are similar.

Lemma 2.8. Let \( V_1 \) and \( V_2 \) be semigroup varieties and \( n \) be a natural number. Then:

(i) \( \text{Perm}_n(V_1 \vee V_2) = \text{Perm}_n(V_1) \wedge \text{Perm}_n(V_2) \);

(ii) if \( V_1 \) and \( V_2 \) are nil-varieties then \( \text{Perm}_n(V_1 \wedge V_2) = \text{Perm}_n(V_1) \vee \text{Perm}_n(V_2) \).

Proof. For brevity, we will denote the identity (1.1) by \( p_n[\pi] \). If a is a word and \( \pi \) is a permutation on the set \( \text{con}(a) \) then we denote by \( \pi[a] \) the word that is obtained from a by the substitution \( x \mapsto \pi(x) \) for every letter \( x \in \text{con}(a) \).

(i) Let \( \pi \in \text{Perm}_n(V_1 \wedge V_2) \). Then the variety \( V_1 \wedge V_2 \) satisfies the identity \( p_n[\pi] \). Hence this identity holds in both the varieties \( V_1 \) and \( V_2 \). Therefore, \( \pi \in \text{Perm}_n(V_1) \) and \( \pi \in \text{Perm}_n(V_2) \), whence \( \pi \in \text{Perm}_n(V_1) \wedge \text{Perm}_n(V_2) \).

Thus, \( \text{Perm}_n(V_1 \wedge V_2) \subseteq \text{Perm}_n(V_1) \wedge \text{Perm}_n(V_2) \). Suppose now that \( \pi \in \text{Perm}_n(V_1) \wedge \text{Perm}_n(V_2) \). Then the identity \( p_n[\pi] \) holds in both the varieties \( V_1 \) and \( V_2 \). Therefore, it holds in \( V_1 \vee V_2 \). Thus, \( \pi \in \text{Perm}_n(V_1 \vee V_2) \) and \( \text{Perm}_n(V_1 \vee V_2) \subseteq \text{Perm}_n(V_1 \vee V_2) \). This implies the required equality.

(ii) Let \( \pi \in \text{Perm}_n(V_1) \vee \text{Perm}_n(V_2) \). Then there is a sequence of permutations \( \pi_1, \pi_2, \ldots, \pi_m \) such that \( \pi = \pi_1 \pi_2 \cdots \pi_m \) and, for each \( i = 1, 2, \ldots, m \), the permutation \( \pi_i \) lies in one of the groups \( \text{Perm}_n(V_1) \) or \( \text{Perm}_n(V_2) \).

Put \( u_0 = x_1 x_2 \cdots x_n \). For each \( i = 1, 2, \ldots, m \), we define by induction the word \( u_i \) by the equality \( u_i = \pi_i[u_{i-1}] \). It is clear that \( u_m = \pi[u_0] \) and the sequence of words \( u_0, u_1, \ldots, u_m \) is a deduction of the identity \( p_n[\pi] \) from identities of the varieties \( V_1 \) and \( V_2 \). This means that \( \pi \in \text{Perm}_n(V_1 \wedge V_2) \).

It remains to verify that \( \text{Perm}_n(V_1 \wedge V_2) \subseteq \text{Perm}_n(V_1) \vee \text{Perm}_n(V_2) \). Let \( \pi \in \text{Perm}_n(V_1 \wedge V_2) \). Then the identity \( p_n[\pi] \) holds in the variety \( V_1 \wedge V_2 \). Let \( u_0, u_1, \ldots, u_m \) be a deduction of this identity from identities of the varieties \( V_1 \) and \( V_2 \). In other words, \( u_0 = x_1 x_2 \cdots x_n \), \( u_m = x_1 x_2 \cdots x_n \) and, for each \( i = 0, 1, \ldots, m - 1 \), the identity \( u_i \approx u_{i+1} \) holds in either \( V_1 \) or \( V_2 \). We will assume that \( u_0, u_1, \ldots, u_m \) is the shortest sequence of words with the mentioned properties. Suppose that there is an index \( i \) such that each \( u_i \) is non-linear or \( \text{con}(u_i) \neq \{ x_1, x_2, \ldots, x_n \} \). Let \( i \) be the least index with such a property. Clearly, \( 0 < i < m \). The word \( u_{i-1} \) is similar to \( x_1 x_2 \cdots x_n \). If \( \text{con}(u_i) \neq \{ x_1, x_2, \ldots, x_n \} \) then there is a letter \( x_j \) that occurs in one of the words \( u_{i-1} \) or \( u_i \) but does not occur in another one. The identity \( u_{i-1} \approx u_i \) holds in one of the varieties \( V_1 \) or \( V_2 \), say, in \( V_1 \). One can substitute 0 for \( x_j \) in \( u_{i-1} \approx u_i \). We obtain that \( x_1 x_2 \cdots x_n \approx 0 \) holds in \( V_1 \), whence \( V_1 \) satisfies the identity \( p_n[\pi] \). In view of Lemma 2.7, the same is true whenever \( \text{con}(u_i) = \{ x_1, x_2, \ldots, x_n \} \) but \( u_i \) is non-linear. But then the sequence of words \( u_0, u_1, \ldots, u_{i-1}, u_m \) is a deduction of the identity \( p_n[\pi] \) from identities of the varieties \( V_1 \) and \( V_2 \) shorter than the deduction \( u_0, u_1, \ldots, u_m \). Therefore,
the words $u_0, u_1, \ldots, u_m$ are linear and $\text{con}(u_i) = \{x_1, x_2, \ldots, x_n\}$ for all $i = 0, 1, \ldots, m$. Hence there are permutations $\pi_1, \pi_2, \ldots, \pi_m \in S_n$ such that $u_i = \pi_i[u_{i-1}]$ for all $i = 1, 2, \ldots, m$ and each of the permutations $\pi_1, \pi_2, \ldots, \pi_m$ lies in either $\text{Perm}_n(V_1)$ or $\text{Perm}_n(V_2)$. Clearly, $\pi = \pi_1\pi_2\cdots\pi_m$, whence $\pi \in \text{Perm}_n(V_1) \lor \text{Perm}_n(V_2)$. □

To verify Proposition 1.2, we need the information about the structure of the subvariety lattice of the group $S_3$. It is generally known and easy to check that this lattice has the form shown in Fig. 1. Here $T$ is the trivial group and $\text{gr}\{\pi\}$ denotes the subgroup of $S_3$ generated by the permutation $\pi$.

To verify Proposition 1.2, we need the information about the structure of the subvariety lattice of the group $S_3$. It is generally known and easy to check that this lattice has the form shown in Fig. 1. Here $T$ is the trivial group and $\text{gr}\{\pi\}$ denotes the subgroup of $S_3$ generated by the permutation $\pi$.

3. The proof of the main results

Proof of Theorem 1.1. Necessity immediately follows from Proposition 2.3 and Lemma 2.5.

Sufficiency. Let $V = M \lor N$ where $M$ is one of the varieties $T$ or $\text{SL}$, while the variety $N$ satisfies one of the identity systems (1.2)–(1.5). We need to verify that the variety $V$ is a modular element in the lattice $\text{SEM}$. In view of Lemma 2.2, we may assume that $M = \text{SL}$, so $V = \text{SL} \lor N$. The same lemma shows that it suffices to prove that $V$ is a modular element of the coideal $[\text{SL}]$ of the lattice $\text{SEM}$. In other words, we have to check that

$$(V \lor Y) \land Z = (V \land Z) \lor Y$$

for arbitrary varieties $Y$ and $Z$ with $\text{SL} \subseteq Y \subseteq Z$. Moreover, it suffices to verify that

$$(V \lor Y) \land Z \subseteq (V \land Z) \lor Y$$

because the opposite inclusion is evident. Thus, we need to prove that if a non-trivial identity $u \approx v$ holds in $(V \land Z) \lor Y$ then it holds in $(V \lor Y) \land Z$ too.

So, let $\text{SL} \subseteq Y \subseteq Z$ and $u \approx v$ be a non-trivial identity that holds in the variety $(V \land Z) \lor Y$. Then $u \approx v$ holds in $Y$ and there is a deduction of this identity from identities of the varieties $V$ and $Z$, that is, a sequence of words (3.1)

$$w_0, w_1, \ldots, w_m$$

such that $w_0 = u$, $w_m = v$ and, for each $i = 0, 1, \ldots, m - 1$, the identity $w_i \approx w_{i+1}$ holds in one of the varieties $V$ or $Z$. We will assume that (3.1)
is the shortest deduction of $u \approx v$ from identities of $V$ and $Z$. In particular, this means that the words $w_0, w_1, \ldots, w_m$ are pairwise distinct, there is no $i \in \{0, 1, \ldots, m - 2\}$ such that $w_i \approx w_{i+1} \approx w_{i+2}$ hold in one of the varieties $V$ or $Z$, and there is no $i \in \{0, 1, \ldots, m - 1\}$ such that $w_i \approx w_{i+1}$ holds in both of these two varieties. Since each of the varieties $V$ and $Z$ contains $SL$, Lemma 2.1 implies that

\begin{equation}
\text{con}(w_0) = \text{con}(w_1) = \cdots = \text{con}(w_m).
\end{equation}

This fact and Lemma 2.1 imply that if, for some $i \in \{0, 1, \ldots, m - 1\}$, the identity $w_i \approx w_{i+1}$ holds in $N$ then it holds in $V$ too. All these observations will be used below without references.

The case $m = 1$ is evident. Indeed, if $m = 1$ then the identity $u \approx v$ holds in one of the varieties $V$ or $Z$. This identity holds also in $Y$, whence it holds in one of the varieties $V \lor Y$ or $Z$, and moreover in $(V \lor Y) \land Z$.

Suppose that $m = 2$. By symmetry, we may assume that $u \approx w_1$ holds in $V$ and $w_1 \approx v$ holds in $Z$. Then $w_1 \approx v \approx u$ hold in $Y$. We see that the identities $u \approx w_1$ and $w_1 \approx v$ hold in $V \lor Y$ and $Z$ respectively, whence $u \approx v$ holds in $(V \lor Y) \land Z$.

At the rest part of the proof we suppose that $m \geq 3$.

First of all, we consider one very special but important partial case.

**Lemma 3.1.** If $m = 3$, the identities $w_0 \approx w_1$ and $w_2 \approx w_3$ hold in the variety $Z$, and the identity $w_1 \approx w_2$ holds in the variety $V$ then the identity $u \approx v$ holds in the variety $(V \lor Y) \land Z$.

**Proof.** Recall that the identity $u \approx v$ holds in $Y$, $u = w_0$ and $v = w_3$. Since $Y \subseteq Z$, we have that $w_1 \approx w_0 \approx w_3 \approx w_2$ hold in $Y$. Therefore, the identity $w_1 \approx w_2$ holds in the variety $V \lor Y$. It remains to take into account that the identities $w_0 \approx w_1$ and $w_2 \approx w_3$ hold in $Z$. \hfill \square

Put

\begin{align*}
Z &= \{w \in F \mid \text{the identity } w \approx 0 \text{ holds in the variety } N\}, \\
L &= \{w \in F \mid \text{the word } w \text{ is linear and } w \notin Z\}, \\
S &= \{w \in F \mid w \notin Z \cup L\}.
\end{align*}

Lemma 2.5 readily implies that if $S \neq \emptyset$ then any word from $S$ is similar to:

- one of the words $x^2$ or $xyz$ whenever $V$ satisfies (1.2);
- the word $x^2$ whenever $V$ satisfies (1.3);
- one of the words $x^2$ or $x^2y$ whenever $V$ satisfies (1.4);
- one of the words $x^2$ or $xy^2$ whenever $V$ satisfies (1.5).

Let $S_k$ be the set of all words from $S$ depending on $k$ letters. We have the following

**Remark 3.2.** $S = S_1 \cup S_2$; if $u \in S_1$ then $u$ is similar to $x^2$; if $u, v \in S_2$ then $u$ and $v$ are similar. \hfill \square

It is evident that each of the words $w_0, w_1, \ldots, w_m$ lies in exactly one of the sets $Z, L$ or $S$. It is clear also that if $w', w'' \in Z$ then $w' \approx w''$ in $N$; if, besides that, $\text{con}(w') = \text{con}(w'')$ then $w' \approx w''$ in $V$. In particular, if $w_i, w_j \in Z$ for
some \( i, j \in \{0, 1, \ldots, m\} \) then \( w_i \approx w_j \) in \( V \). All these observations will be used below without references.

One can provide some properties of the sequence (3.1).

**Lemma 3.3.** If \( w_i, w_j \in Z \) for some \( 0 \leq i < j \leq m \) then \( j = i + 1 \). In particular, the sequence (3.1) contains at most two words from the set \( Z \).

**Proof.** The identity \( w_i \approx w_j \) holds in the variety \( V \). If \( j > i + 1 \) then the sequence of words

\[
w_0, w_1, \ldots, w_i, w_j, \ldots, w_m
\]

is a deduction of the identity \( u \approx v \) from identities of the varieties \( V \) and \( Z \) shorter than the sequence (3.1). \( \square \)

**Lemma 3.4.** If \( w_i \in S_1 \) for some \( i \in \{0, 1, \ldots, m\} \) then:

(i) either \( i = 0 \) or \( i = m \);

(ii) if \( i = 0 \) [respectively \( i = m \)] then the identity \( w_0 \approx w_1 \) [respectively \( w_{m-1} \approx w_m \)] holds in the variety \( Z \).

**Proof.** In view of Remark 3.2, we may assume without loss of generality that \( w_i = x^2 \). Suppose that \( 0 < i < m \). Then \( w_i \approx w_j \) holds in \( V \) for some \( j \in \{i-1, i+1\} \). In particular, \( w_i \approx w_j \) in \( N \). Since \( \text{con}(w_j) = \text{con}(w_i) = \{x\} \) and \( w_j \neq w_i \), we have that \( w_j^k = x^k \) for some \( k \neq 2 \). It is evident that \( x^k \approx x^2 \) implies \( x^2 \approx 0 \) in any nil-variety. Therefore, \( w_i \approx 0 \) holds in \( N \) contradicting the claim \( w_j \approx 0 \). The claim (i) is proved. Analogous arguments show that if \( i = 0 \) [respectively \( i = m \)] then the identity \( w_0 \approx w_1 \) [respectively \( w_{m-1} \approx w_m \)] fails in \( V \) and therefore, holds in \( Z \). The claim (ii) is proved as well. \( \square \)

**Lemma 3.5.** If the sequence (3.1) does not contain a word from the set \( S_2 \) and \( w_i \in L \) for some \( i \in \{1, \ldots, m-1\} \) then either \( w_{i-1} \in L \) or \( w_{i+1} \in L \).

**Proof.** Arguing by contradiction, suppose that \( w_{i-1}, w_{i+1} \in Z \cup S \). If \( w_{i-1} \in S \) then \( w_{i-1} \in S_1 \) and Lemma 3.4 applies with the conclusion that the identity \( w_{i-1} \approx w_i \) holds in \( Z \). Let now \( w_{i-1} \in Z \). Then the variety \( N \) satisfies the identity \( w_{i-1} \approx 0 \). On the other hand, the identity \( w_i \approx 0 \) fails in \( N \) because \( w_i \in L \). Therefore, the identity \( w_{i-1} \approx w_i \) fails in \( V \), whence it holds in \( Z \). We see that \( w_{i-1} \approx w_i \) holds in \( Z \) in any case. Analogous arguments show that \( w_i \approx w_{i+1} \) holds in \( Z \). Thus, \( w_{i-1} \approx w_i \approx w_{i+1} \) hold in \( Z \) that is impossible. \( \square \)

**Lemma 3.6.** If the sequence (3.1) does not contain a word from the set \( S_2 \) and \( w_i, w_{i+1} \in L \) for some \( i \in \{0, 1, \ldots, m-1\} \) then the sequence (3.1) does not contain words from the set \( Z \).

**Proof.** Suppose that \( i+1 < m \) and \( w_{i+2} \in Z \). Then the variety \( N \) satisfies the identity \( w_{i+2} \approx 0 \) but does not satisfy the identity \( w_{i+1} \approx 0 \). Hence the identity \( w_{i+1} \approx w_{i+2} \) is false in \( N \), and moreover in \( V \). Therefore, \( w_{i+1} \approx w_{i+2} \) holds in \( Z \), whence \( w_i \approx w_{i+1} \) holds in \( V \). Clearly, \( w_i = \sigma(w_{i+1}) \) for some permutation \( \sigma \) on the set \( \text{con}(w_{i+1}) \). Then \( w_i = \sigma(w_{i+1}) \approx \sigma(w_{i+2}) \) holds in \( Z \). Since \( w_{i+2} \approx 0 \) holds in \( N \), we have that \( \sigma(w_{i+2}) \approx 0 \) holds in \( N \) too. Thus \( \sigma(w_{i+2}) \approx w_{i+2} \) holds in \( N \) and therefore, in \( V \). Recall that \( m \geq 3 \). Hence
either $i > 0$ or $i + 2 < m$. If $i > 0$ then $w_{i-1} \approx w_i \approx \sigma[w_{i+2}]$ hold in $Z$ and the sequence of words

$$w_0, w_1, \ldots, w_{i-1}, \sigma[w_{i+2}], w_{i+2}, \ldots, w_m$$

is a deduction of the identity $u \approx v$ from identities of the varieties $V$ and $Z$ shorter than the sequence (3.1). Further, if $i + 2 < m$ then $\sigma[w_{i+2}] \approx w_{i+2} \approx w_{i+3}$ hold in $V$ and we also have a deduction of the identity $u \approx v$ from identities of the varieties $V$ and $Z$ shorter than the sequence (3.1), namely the sequence of words

$$w_0, w_1, \ldots, w_i, \sigma[w_{i+2}], w_{i+3}, \ldots, w_m.$$ 

Both these cases are impossible. We prove that if $i + 1 < m$ then $w_{i+2} \notin Z$. By symmetry, if $i > 0$ then $w_{i-1} \notin Z$.

Let now $w_j, w_{j+1}, \ldots, w_{j+k}$ (where $0 \leq j < j + k \leq m$) be the maximal subsequence of the sequence (3.1) consisting of words from the set $L$. In other words, $w_j, w_{j+1}, \ldots, w_{j+k} \in L$, $w_{j+k+1} \notin L$ whenever $j + k < m$, and $w_{i-1} \notin L$ whenever $j > 0$. Suppose that $j + k < m$. As we have seen in the previous paragraph, this implies that $w_{j+k+1} \notin Z$, whence $w_{j+k+1} \in S$. Now Lemma 3.4(i) applies, and we conclude that $j + k + 1 = m$. Analogously, if $j > 0$ then $j = 1$ and $w_0 \in S$. We see that words from the set $Z$ are absent in the sequence (3.1).}

Further considerations are divided into two cases.

Case 1: the sequence (3.1) does not contain a word from the set $S_2$. Suppose at first that the sequence (3.1) does not contain adjacent words from the set $L$. Lemmas 3.4(i) and 3.5 imply that $w_1, \ldots, w_{m-1} \in Z$ in this case, whence $w_1 \approx \cdots \approx w_{m-1} \in V$. Therefore, $m - 1 = 2$, that is, $m = 3$. Since the identity $w_1 \approx w_2$ holds in $V$, the identities $w_0 \approx w_1$ and $w_2 \approx w_3$ hold in $Z$. Now Lemma 3.1 applies and we are done.

Suppose now that the sequence (3.1) contains adjacent words from the set $L$ but does not contain three words in row from this set. By Lemma 3.6 the sequence (3.1) does not contain words from the set $Z$. Then Lemma 3.4(i) implies that $m = 3$, $w_0, w_3 \in S$ and $w_1, w_2 \in L$. By Lemma 3.4(ii) the identities $w_0 \approx w_1$ and $w_2 \approx w_3$ hold in $Z$. Therefore, $w_1 \approx w_2$ holds in $V$ and Lemma 3.1 applies again.

Finally, suppose that the sequence (3.1) contains three words in row from the set $L$. Let $w_i, w_{i+1}, w_{i+2} \in L$ for some $i \in \{0, 1, \ldots, m - 2\}$. Put $k = \ell(w_i)$. In view of (3.2), we have $\ell(w_{i+1}) = \ell(w_{i+2}) = k$. One of the identities $w_i \approx w_{i+1}$ or $w_{i+1} \approx w_{i+2}$ holds in the variety $V$, whence it holds in $N$.

Suppose that $k = 2$. The variety $N$ is commutative in this case. Then $N$ is a modular element of $SEM$ by Proposition 2.4 and therefore, $V$ has the same property by Lemma 2.2.

Let now $k \geq 3$. We may assume without loss of generality that $\text{con}(w_j) = \{x_1, x_2, \ldots, x_k\}$ for all $j = 0, 1, \ldots, m$. According to Lemma 3.6 the sequence (3.1) does not contain words from the set $Z$. Further, by Remark 3.2 if $w \in S$ then $w$ is similar to $x^2$, whence $\text{con}(w) \neq \{x_1, x_2, \ldots, x_k\}$. Hence (3.1) does not contain words from the set $S$. Therefore, $w_0, w_1, \ldots, w_m \in L$. 

Suppose that $k = 3$. Since $w_i \approx w_{i+1}$ holds in $Z$ for some $i \in \{0, 1, \ldots, m - 1\}$, the variety $Z$ satisfies a permutational identity of length 3. In other words, the group $\text{Perm}_3(Z)$ contains some non-trivial permutation $\sigma$. It is clear that $w_m = \tau[w_0]$ for some permutation $\tau \in S_3$. The permutation $\tau$ is non-trivial because the identity $u \approx v$ is non-trivial. If $\tau \in \text{Perm}_3(Z)$ then the identity $w_0 \approx w_m$ (that is, $u \approx v$) holds in the variety $Z$ and therefore, in $(V \vee Y) \wedge Z$. Suppose now that $\tau \notin \text{Perm}_3(Z)$. The identity $u \approx v$ has the form $u \approx \tau[u]$. Recall that this identity holds in the variety $Y$, whence $\tau \in \text{Perm}_3(Y)$. Besides that, $\sigma \in \text{Perm}_3(Y)$ because $Y \subseteq Z$. Since $\tau \notin \text{Perm}_3(Z)$, we have that $\sigma$ and $\tau$ generate distinct non-trivial subgroups of $S_3$. Therefore, the subgroup of $S_3$ generated by these two permutations coincides with $S_3$ (see Fig. 1), that is, $\text{Perm}_3(Y) = S_3$. In other words, $Y$ satisfies all permutational identities of length 3. This means that, for each $i = 0, 1, \ldots, m - 1$, the identity $w_i \approx w_{i+1}$ holds in one of the varieties $V \vee Y$ or $Z$, whence $u \approx v$ holds in $(V \vee Y) \wedge Z$.

Finally, let $k \geq 4$. The identity $u \approx v$, that is, $w_0 \approx w_m$ is a permutational identity of length $k$. In other words, there is a permutation $\xi \in S_k$ with $v = \xi[u]$. If $N$ satisfies one of the identity systems (1.2) or (1.3) then the claim 1(iii) of Lemma 2.6 applies with the conclusion that $\xi \in \text{Perm}_k(N)$. This means that the identity $u \approx v$ holds in $N$ and therefore, in $V$. In this case $u \approx v$ holds in $V \vee Y$, and moreover in $(V \vee Y) \wedge Z$. By symmetry, it remains to consider the case when $N$ satisfies the identity system (1.4).

Suppose that $k = 4$. In view of the claim 1(i) of Lemma 2.6, $\text{Perm}_4(N) \supseteq \text{Stab}_4(4)$. Besides that, $N$ satisfies the identity $x y z t \approx x z t y$, whence the group $\text{Perm}_4(N)$ contains the permutation (234). Since this permutation does not lie in $\text{Stab}_4(4)$ and $\text{Stab}_4(4)$ is a maximal proper subgroup in $S_4$, we have that $\text{Perm}_4(N) = S_4$. Further, let $k \geq 5$. Then the claims 1(i) and 2 of Lemma 2.6 imply that the group $\text{Perm}_k(N)$ contains both the groups $\text{Stab}_k(1)$ and $\text{Stab}_k(k)$, whence $\text{Perm}_k(N) = S_k$. Thus, the last equality holds for any $k \geq 4$. In particular, $\xi \in \text{Perm}_k(N)$ in this case. As we have already seen in the previous paragraph, this implies the requirement conclusion.

Case 2: the sequence (3.1) contains a word from the set $S_2$. All words from $S_2$ depend on two letters. In view of (3.2), we may assume that $\text{con}(w_i) = \{x, y\}$ for each $i = 0, 1, \ldots, m$. In particular, the sequence (3.1) does not contain words from the set $S_1$. Besides that, Remark 3.2 shows that if $w_i, w_j \in S_2$ for some $0 \leq i < j \leq m$ then the words $w_i$ and $w_j$ are similar. Since words from $S_2$ depend on two letters, this implies that the sequence (3.1) contains at most two words from the set $S_2$. All these observations will be used below without references. We need two additional lemmas.

**Lemma 3.7.** If the sequence (3.1) contains a word from the set $S_2$, $w_i \in L$ for some $i \in \{0, 1, \ldots, m\}$ and the variety $V$ satisfies a non-trivial identity of the form $w_i \approx w$ then the variety $V$ is a modular element in $SEM$.

**Proof.** The word $w_i$ is linear and $\text{con}(w_i) = \{x, y\}$. Therefore, $w_i \in \{x y, y x\}$. We may assume without loss of generality that $w_i = x y$. The identity $x y \approx w$ holds in the variety $N$. If $w = y x$ then the variety $N$ is a modular element in $SEM$ by Proposition 2.4, whence the variety $V$ has the same property by Lemma 2.2. Suppose now that $w \neq y x$. Then $\ell(w) \neq 2$. By Lemma 2.7 $x y \approx 0$
holds in $\mathbb{N}$. Then the variety $V = SL \lor N$ is a neutral element of the lattice $SEM$ by [12, Proposition 4.1]. Therefore, the variety $V$ is a modular element in $SEM$. □

Lemma 3.8. If the variety $V$ satisfies the identity $w_i \approx w_{i+1}$ for some $i \in \{0, 1, \ldots, m - 1\}$ and one of the words $w_i$ or $w_{i+1}$ lies in $S_2$ then either the variety $V$ is a modular element in $SEM$ or both the words $w_i$ and $w_{i+1}$ lie in $S_2$.

Proof. We may assume without loss of generality that $w_i \in S_2$. If $w_{i+1} \in Z$ then $w_i \approx w_{i+1} \approx 0$ in $N$ contradicting the claim $w_i \in S$. Further, if $w_{i+1} \in L$ then Lemma 3.7 applies with the conclusion that the variety $V$ is a modular element in $SEM$. Finally, if $w_{i+1} \notin Z \cup L$ then $w_{i+1} \in S$. Since the sequence (3.1) does not contain words from the set $S_1$, we have that $w_{i+1} \in S_2$. □

Suppose now that the sequence (3.1) contains only one word from the set $S_2$. Namely, let $w_i \in S_2$. Suppose that $i \in \{1, \ldots, m - 1\}$. Then the variety $V$ satisfies one of the identities $w_{i-1} \approx w_i$ or $w_i \approx w_{i+1}$. Since $w_{i-1}, w_{i+1} \notin S_2$, Lemma 3.8 implies that the variety $V$ is a modular element in $SEM$. It remains to consider the case when either $i = 0$ or $i = m$. By symmetry, we may suppose that $i = 0$. Then $w_j \notin S$ for all $j = 1, 2, \ldots, m$. If the identity $w_0 \approx w_1$ holds in $V$ then we may apply Lemma 3.8 and conclude that the variety $V$ is a modular element in $SEM$. Suppose now that the identity $w_0 \approx w_1$ holds in $Z$. Then $w_1 \approx w_2$ in $V$. In view of Lemma 3.7, we may assume that $w_2 \notin L$. Therefore, $w_2 \in Z$. Further, $w_2 \approx w_3$ in $Z$. If $m = 3$ then Lemma 3.1 applies with the required conclusion. Otherwise, $w_3 \approx w_4$ in $V$. Lemma 3.7 allows us to assume that $w_4 \notin L$, whence $w_4 \in Z$. Therefore, $w_2 \approx w_4$ in $V$. This means that the sequence of words

$$w_0, w_1, w_2, w_4, \ldots, w_m$$

is a deduction of the identity $u \approx v$ from identities of the varieties $V$ and $Z$ shorter than (3.1).

Finally, suppose that the sequence (3.1) contains two words from the set $S_2$. Suppose at first that $w_i \in S_2$ for some $i \in \{1, \ldots, m - 1\}$. Then the variety $V$ satisfies the identity $w_i \approx w_j$ for some $j \in \{i - 1, i + 1\}$. In view of Lemma 3.8, we may assume that $w_j \in S_2$ in this case. Suppose now that $w_i \notin S_2$ whenever $i \in \{1, \ldots, m - 1\}$. Then $w_0, w_m \in S_2$. If, besides that, at least one of the identities $w_0 \approx w_1$ or $w_m-1 \approx w_m$ holds in the variety $V$ then Lemma 3.8 applies and we conclude that $V$ is a modular element in $SEM$. We see that either $w_0, w_m \in S_2$ and the identities $w_0 \approx w_1$ and $w_{m-1} \approx w_m$ hold in $Z$ or $w_i, w_{i+1} \in S_2$ for some $i \in \{0, 1, \ldots, m - 1\}$ and $w_i \approx w_{i+1}$ holds in $V$.

Suppose that $w_0, w_m \in S_2$ and the identities $w_0 \approx w_1$ and $w_{m-1} \approx w_m$ hold in $Z$. Then $w_1, w_m-1 \notin S$. The identities $w_1 \approx w_2$ and $w_{m-2} \approx w_{m-1}$ hold in the variety $V$. Lemma 3.7 permits to assume that $w_1, w_m-1 \notin L$. Since $w_1, w_m-1 \notin S$, we have $w_1, w_m-1 \in Z$. Then $w_1 \approx w_m-1$ holds in $V$. This means that the sequence of words

$$w_0, w_1, w_m-1, w_m$$
is a deduction of the identity $u \approx v$ from identities of the varieties $V$ and $Z$. If $m > 3$ then this deduction shorter than (3.1), while if $m = 3$ then Lemma 3.1 applies.

It remains to consider the case when $w_i, w_{i+1} \in S_2$ for some $i \in \{0, 1, \ldots, m-1\}$ and $w_i \approx w_{i+1}$ holds in $V$. Suppose at first that $m-3 < i < 2$. Since $m \geq 3$, we have $m = 3$ and $i = 1$. Then the identity $w_1 \approx w_2$ holds in $V$, whence the identities $w_0 \approx w_1$ and $w_2 \approx w_3$ hold in $Z$. Now Lemma 3.1 applies. So, we may assume that either $i \geq 2$ or $i \leq m-3$. By symmetry, it suffices to consider the former case. So, let $i \geq 2$. Then the identity $w_{i-1} \approx w_i$ holds in $Z$, while the identity $w_{i-2} \approx w_{i-1}$ holds in $V$. Clearly, $w_{i-1} \notin S$. Besides that, Lemma 3.7 allows us to assume that $w_{i-1} \notin L$. Therefore, $w_{i-1} \in Z$. Since $w_{i-2} \approx w_{i-1}$ holds in $V$, this identity holds also in $N$. Hence $w_{i-2} \approx w_{i-1} \approx 0$ hold in $N$, that is $w_{i-2} \in Z$. Let $\pi$ be a unique non-trivial permutation on the set $\{x, y\}$. Remark 3.2 implies that $w_{i+1} = \pi[w_i]$. Since the variety $Z$ satisfies the identity $w_{i-1} \approx w_i$, it satisfies also the identity $\pi[w_{i-1}] \approx \pi[w_i]$, that is $\pi[w_{i-1}] \approx w_{i+1}$. Further, the variety $N$ satisfies the identity $\pi[w_{i-1}] \approx 0$ because it satisfies $w_{i-1} \approx 0$. Thus, the identity $w_{i-2} \approx \pi[w_{i-1}]$ holds in $N$ and therefore, in $V$. We see that the sequence of words

$$w_0, w_1, \ldots, w_{i-2}, \pi[w_{i-1}], w_{i+1}, \ldots, w_m$$

is a deduction of the identity $u \approx v$ from identities of the varieties $V$ and $Z$ shorter than (3.1).

We complete the proof of Theorem 1.1.  

Proof of Proposition 1.2. Put

$$V = \var{xyzt \approx xyx \approx x^2 \approx 0, x_1x_2x_3 \approx x_1x_2x_3, x_1x_2x_3 \approx x_1x_2x_3}.$$  

The variety $V$ satisfies one of the identity systems (1.2)–(1.5). According to Theorem 1.1 $V$ is a modular element in the lattice $SEM$. It remains to check that $V$ is not a cancellable element of this lattice. Let $\sigma$ and $\tau$ be non-trivial permutations from $S_3$ such that the groups $gr\{\rho\}$, $gr\{\sigma\}$ and $gr\{\tau\}$ are pairwise distinct. Put

$$X = \var{xyzt \approx xyx \approx x^2 \approx 0, x_1x_2x_3 \approx x_1x_2x_3, x_1x_2x_3 \approx x_1x_2x_3},$$

$$Y = \var{xyzt \approx xyx \approx x^2 \approx 0, x_1x_2x_3 \approx x_1x_2x_3, x_1x_2x_3 \approx x_1x_2x_3}.$$  

Clearly, $X \neq Y$. It is evident that $Perm_3(V) = gr\{\rho\}$, $Perm_3(X) = gr\{\sigma\}$ and $Perm_3(Y) = gr\{\tau\}$. Lemma 2.8(ii) and Fig. 1 imply that

$$Perm_3(V \land X) = Perm_3(V) \lor Perm_3(X) = S_3.$$  

This means that the variety $V \land X$ satisfies all permutational identities of length 3. Hence $V \land X \subseteq Y$ and therefore, $V \land X \subseteq V \land Y$. The opposite inclusion is verified analogously, whence $V \land X = V \land Y$.

It remains to verify that $V \lor X = V \lor Y$. Suppose that an identity $u \approx v$ holds in the variety $V \lor X$. We are going to check that then this identity holds in $Y$. We can assume that the identity $u \approx v$ is non-trivial because the required conclusion is evident in the contrary case. If each of the words $u$ and $v$ either is non-linear or has the length $> 3$ then $u \approx 0 \approx v$ hold in $Y$. Let now $u$ and $v$ be linear words of length $\leq 3$. If $con(u) \neq con(v)$ then $u \approx 0 \approx v$ hold in $Y$ again
because $Y$ is a nil-variety. Therefore, we can assume that $\text{con}(u) = \text{con}(v)$. In particular, this means that $\ell(u) = \ell(v)$. Clearly, $\ell(u) > 1$ because the identity $u \approx v$ is trivial otherwise. If $\ell(u) = 2$ then $u \approx v$ is the commutative law. But then $u \approx v$ is false in $V$, and moreover in $V \lor X$. Finally, suppose that $\ell(u) = 3$. Then $u \approx v$ is a permutational identity of length 3. Lemma 2.8(i) and Fig. 1 imply that

$$\text{Perm}_3(V \lor X) = \text{Perm}_3(V) \land \text{Perm}_3(X) = T.$$ 

Therefore, the identity $u \approx v$ is trivial. We have a contradiction. Thus, $u \approx v$ holds in $Y$. Hence $V \lor X \supseteq Y$ and therefore, $V \lor X \supseteq V \lor Y$. The opposite inclusion is verified analogously, whence $V \lor X = V \lor Y$ and we are done. \hfill $\square$

**Acknowledgments.** The authors express their thanks to Dr. V. Shaprynskii for fruitful discussions.

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