POLYNOMIAL IDENTITIES OF INCIDENCE
ALGEBRAS

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Abstract. In this paper we determine the polynomial identities satisfied by
incidence algebras. One of our results is logically equivalent to the Amitsur-
Levitzki Theorem on the polynomial identities satisfied by \( K_n \), the algebra of
of \( n \times n \) matrices over a field \( K \).

0. Preliminaries. The incidence algebra of a finite quasi-ordered set of
cardinality \( n \) has a natural embedding in \( K_n \), the algebra of \( n \times n \) matrices over
the ground field \( K \). The polynomial identities (P.I.) satisfied by \( K_n \) have been
determined by the famous theorem of Amitsur and Levitzki. In the spirit of
generalization it is thus natural to consider the P.I. satisfied by incidence
algebras. We do this here, obtaining a result which is in fact logically
equivalent to the Amitsur-Levitzki Theorem.

Let \( Q \) be a locally finite quasi-ordered (q.o.) set, i.e., \( Q \) has a relation \( r \) which
is reflexive and transitive and for which every segment \([x,y] = \{z \in Q; x \leq z \leq y\}\) is finite. The incidence algebra \( I(Q) \) of \( Q \) over a field \( K \) is the
associative unital algebra of functions \( f: Q \times Q \rightarrow K \) with the property that
\( f(x,y) \neq 0 \Rightarrow x \leq y \), under the product

\[
f \ast g(x,y) = \sum_{x \leq z \leq y} f(x,z)g(z,y).
\]

The unit \( \delta \) of \( I(Q) \) is defined by

\[
\delta(x,y) = \begin{cases} 
1 & \text{if } x = y, \\
0 & \text{if } x \neq y.
\end{cases}
\]

For \( x \leq y \in Q \), define \( \delta_{xy} \in I(Q) \) by

\[
\delta_{xy}(u,v) = \begin{cases} 
1 & \text{if } x = u, y = v, \\
0 & \text{otherwise},
\end{cases}
\]

and set \( e_x = \delta_{xx} \). Then \( \{\delta_{xy}\}_{x \leq y} \) is a linearly independent subset of \( I(Q) \), and
every element of \( I(Q) \) may be regarded as a formal linear combination of

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possibly infinitely many elements from this set, using suitable topological notions. See [1, §3] or [2, §1] for more details.

If $Q$ is of finite cardinality $n$, then $I(Q)$ has a natural embedding $\varphi$ in $K_n$. This is obtained as follows: assume $Q = \{x_i\}_{i=1}^n$, where $x_i \leq x_j$ or $x_j \leq x_i$ (such a labelling is always possible by a simple application of Szpilrajn's Lemma). Then to $f \in I(Q)$ we assign the matrix $\varphi f \in K_n$ defined by $(\varphi f)_{uv} = f(x_u, x_v)$, for $1 \leq u, v \leq n$. In the case when $Q$ is the q.o. set in which $x_i \leq x_j$, $1 \leq i, j \leq n$, the embedding $\varphi$ is in fact onto, so that $I(Q) \simeq K_n$.

We now review some basic notions and facts on polynomial identities. See [3, Chapter 1] for more details.

Let $A$ be an associative unital algebra over a field $K$. We say that $A$ satisfies a polynomial identity of degree $k$ if there exists a polynomial $h(x_1, \ldots, x_k)$ in the $k$ noncommuting indeterminates $x_1, \ldots, x_k$ such that $h(ax_1, \ldots, ak) = 0 \forall a_1, \ldots, a_k \in A$. The standard polynomial of degree $k$ is defined by

$$[x_1, \ldots, x_k] = \sum_{\sigma \in S_k} \text{sgn} \sigma x_{\sigma_1} \cdots x_{\sigma_k},$$

where $S_k$ is the symmetric group on $k$ letters and sgn $\sigma$ denotes the parity of the permutation $\sigma$. The algebra $A$ satisfies the standard polynomial identity of degree $k$, abbreviated S.P.I. (k), if $[a_1, \ldots, a_k] = 0 \forall a_1, \ldots, a_k \in A$.

It may be shown that if $A$ satisfies a nontrivial polynomial identity of degree $k$, then $A$ satisfies the polynomial identity $p(a_1, \ldots, a_k) = 0 \forall a_1, \ldots, a_k \in A$, where

$$p(x_1, \ldots, x_k) = x_1 x_2 \cdots x_k + \sum_{\sigma \in S_k; \sigma \neq 1} c(\sigma) x_{\sigma_1} \cdots x_{\sigma_k},$$

for $c(\sigma) \in K$. In addition, the standard polynomial of degree $k$ is multilinear and skew-symmetric in its arguments. Finally, the algebra $K_n$ satisfies no P.I. of degree $< 2n$ and satisfies S.P.I. (2n) (the latter statement being the Amitsur-Levitzki Theorem).

1. Results. We now discuss P.I. for incidence algebras.

Definition. A multichain of length $n$ in a quasi-ordered set $Q$ is a sequence of elements $\{x_0, \ldots, x_n\}$ of $Q$ such that $x_i \leq x_{i+1}$, for $0 \leq i \leq n - 1$. A chain of length $n$ is a multichain in which all the elements are distinct.

Our results consist in relating the above concepts to P.I. of incidence algebras.

Theorem 1. Let $Q$ be a locally finite q.o. set. If $Q$ has a chain of length $n - 1$, then $I(Q)$ satisfies no P.I. of degree $< 2n$.

Proof. Let $\{z_0, z_1, \ldots, z_{k-1}\}$ be a chain of length $k - 1$ in $Q$, where $k \leq n$. Then

$$e_{z_0} \cdot \delta_{z_0 z_1} \cdot e_{z_1} \cdot \cdots \cdot e_{z_{k-2}} \cdot \delta_{z_{k-2} z_{k-1}} \cdot e_{z_{k-1}}$$

is the product of $2k - 1$ terms of $I(Q)$ with value

$$\delta_{z_0 z_{k-1}} \neq 0.$$
But any rearrangement in the order of the factors results in zero product. Thus

\[ p(e_{z_0}, \delta_{z_0 z_1}, e_{z_1}, \ldots, \delta_{z_{k-2} z_{k-1}}, e_{z_{k-1}}) \neq 0, \]

for any polynomial \( p \) of the form (*) above. Therefore \( \text{span}\{e_{z_0}, \delta_{z_0 z_1}, \ldots, e_{z_{k-1}}\} \) cannot satisfy a P.I. of degree \( 2k - 1 \), for \( k \leq n \). Hence \( I(Q) \) can satisfy no P.I. of odd degree \( < 2n \).

Consider now

\[ e_{z_0} \ast \delta_{z_0 z_1} \ast e_{z_1} \ast \ldots \ast e_{z_{k-2}} \ast \delta_{z_{k-2} z_{k-1}}. \]

This is the product of \( 2k - 2 \) terms of \( I(Q) \) with value

\[ \delta_{z_0 z_{k-1}} \neq 0, \]

but any rearrangement in the order of the factors results in zero product. Reasoning as above, we obtain that

\[ \text{span}\{e_{z_0}, \delta_{z_0 z_1}, \ldots, \delta_{z_{k-2} z_{k-1}}\} \]

cannot satisfy a P.I. of degree \( 2k - 2 \), for \( k \leq n \). Hence \( I(Q) \) can satisfy no P.I. of even degree \( < 2n \). This completes proof of the theorem. \( \square \)

Note that if \( Q \) is the q.o. set \( \{x_1\}_{i=1}^n \), where \( x_i \neq x_j, 1 \leq i, j \leq n \), then \( I(Q) \approx K_n \) and \( Q \) has (in fact consists of) a chain of length \( n - 1 \). Hence an immediate corollary of Theorem 1 is the above-cited result, that \( K_n \) satisfies no P.I. of degree \( < 2n \).

**Theorem 2.** Let \( Q \) be locally finite. If all chains of \( Q \) have length \( \leq n - 1 \), then \( I(Q) \) satisfies S. P. I. \( (2n) \).

**Proof.** By our preliminary remarks it suffices to show that

\[ [\delta_{x_1 y_1}, \ldots, \delta_{x_{2n} y_{2n}}] = 0, \]

for all choices of

\[ \{\delta_{x_i y_i}\}_{i=1}^{2n} \subseteq I(Q). \]

We may assume without loss of generality that \( y_1 = x_2, \ldots, y_{2n-1} = x_{2n} \), under suitable relabelling if necessary, otherwise all terms of

\[ [\delta_{x_1 y_1}, \ldots, \delta_{x_{2n} y_{2n}}] \]

are 0 and hence \( [\delta_{x_1 y_1}, \ldots, \delta_{x_{2n} y_{2n}}] = 0 \) automatically. Under this assumption we have \( x_1 \neq y_1 \neq x_2 \neq y_2 \neq \ldots \neq y_{2n} \), so that \( \{x_1, y_1, \ldots, y_{2n}\} \) is a multichain of length \( 2n \).

Discarding repeats, there exists a chain of length \( m \leq 2n \), say \( \{z_0, \ldots, z_m\} \), which contains the same elements as \( \{x_1, y_1, \ldots, y_{2n}\} \). By hypothesis, \( m \leq n - 1 \). Let \( Q' \) be the quasi-ordered set consisting of the elements of this chain. Then

\[ \{\delta_{x_1 y_1}, \ldots, \delta_{x_{2n} y_{2n}}\} \subseteq I(Q'), \]
and hence every term of $[\delta_{x_1y_1}, \ldots, \delta_{x_{2n}y_{2n}}]$ is an element of $I(Q')$. Since $I(Q') \subseteq K_{m+1} \subseteq K_n$ as noted above, $I(Q')$ satisfies S.P.I.(2n). Therefore $[\delta_{x_1y_1}, \ldots, \delta_{x_{2n}y_{2n}}] = 0$ and we conclude that $I(Q)$ satisfies S.P.I.(2n). □

Note again that if $Q$ is the q.o. set $\{x_i\}_{i=1}^n$, where $x_i \neq x_j$, $1 \leq i, j \leq n$, then $I(Q) = K_n$ and all chains of $Q$ have length $\leq n - 1$. Hence an immediate corollary of Theorem 2 is the Amitsur-Levitzki Theorem, that $K_n$ satisfies S.P.I.(2n). But since the Amitsur-Levitzki Theorem is used in the proof of Theorem 2, we must conclude that the two theorems are logically equivalent.

REFERENCES


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