Finitely Presented Algebras and the Polynomial Time Hierarchy*

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Abstract

Let $S_n(V_n) = \langle \Gamma, Q_1 v_1 \ldots Q_k v_k \ s \equiv j \rangle$ |

$\Gamma$ is a finite presentation of $\mathcal{A}$, $Q_1 \ldots Q_k$ is a string of quantifiers with $n$ alternations, the outermost an $3(v)$, $\mathcal{A} \vdash Q_1 v_1 \ldots Q_k v_k \ s \equiv t$.

It is shown that $S_n(V_n)$ is complete for $\mathcal{P}^P_n(\Pi^P_n)$, and $\bigcup_{n=0}^{\infty} S_n \cup V_n$ is complete for PSPACE, answering a question of [1] and generalizing a result of Stockmeyer and Meyer [2].

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0. Introduction

In [1] we discussed the importance of finitely presented algebras with respect to finite tree automata, context free derivations, and logic. We showed that several decision problems previously known to be complete for various complexity classes were in fact special cases of natural decision problems about finitely presented algebras. Here we continue on this track.

Stockmeyer and Meyer [2] proved that deciding truth of closed quantified Boolean expressions with \(n\) alternations of quantifiers, \(n\not=1\), the outermost a \(\exists(V)\), is a problem complete for \(\mathbb{P}^\mathbb{P}_n\), the \(n\)th \(\Sigma(\Pi)\) level of the polynomial time hierarchy. There is, however, a pathological twist to their result, namely that it fails for \(n=0\), since Boolean trees can be evaluated in deterministic logspace. This suggests that sets of quantified Boolean expressions are perhaps not the proper canonical complete sets for \(\mathbb{P}^\mathbb{P}_n\) and \(\Pi^\mathbb{P}_n\).

In this paper we answer a question left open in [1] and generalize the result of Meyer and Stockmeyer mentioned above. Let

\[
S_n(V) = \{ <\Gamma, Q_1v_1...Q_kv_k, s\in\Gamma> \mid \\
\Gamma \text{ is a finite presentation of } \mathcal{A}, Q_1...Q_k \text{ is a string of quantifiers with } n \text{ alternations, the outermost} \\
an \exists(V), \text{ the sentence } Q_1v_1...Q_kv_k, s\in\Gamma \text{ is true in } \mathcal{A} \}.
\]
Sets of quantified Boolean expressions are special cases of these sets, since \( \Gamma \) can be taken to present the two-element Boolean algebra. We show that \( S_n(V_n) \) is \( \leq^m_{\log} \)-complete for \( \tau_n^P(2^P) \), and \( \bigcup_{n=0}^\omega S_n \cup V_n \) is \( \leq^m_{\log} \)-complete for PSPACE. The pathology noted above disappears, since as shown in [1], \( S_0(V_0) \) is \( \leq^m_{\log} \)-complete for P.
1. Preliminaries

We will review briefly the basic definitions. The reader should consult [1] for a more extensive treatment.

Definition 1.0

An algebra $\mathcal{A}$ is finitely presented if there is a finite set $G$ of generator symbols, a finite set $O$ of operator symbols of various finite arities, and a finite set $\Gamma$ of axioms or defining relations of the form $x=y$, where $x$ and $y$ are terms over $G$ and $O$, such that $\mathcal{A}$ is isomorphic to the free algebra (algebra of terms) over $G$ and $O$ modulo the congruence induced by $\Gamma$. The triple $\langle G, O, \Gamma \rangle$ is a presentation of $\mathcal{A}$.

Example 1.1

The two-element Boolean algebra is presented by

$G = \{0, 1\}$

$O = \{\land, \lor, \neg\}$

$\Gamma = \{0 \lor 0 \equiv 0, \ 0 \lor 1 \equiv 1, \ 1 \lor 0 \equiv 1, \ 1 \lor 1 \equiv 1,$

$\land 0 \equiv 0, \ \land 1 \equiv 0, \ \land 0 \equiv 0, \ \land 1 \equiv 1,$

$\neg 1 \equiv 0, \ \neg 0 \equiv 1\}$.}

For computational purposes we shall consider terms to be represented by labeled dags, e.g. the term $0 \lor 1$ would be represented by the tree

```
    0
   /|
  / 1
 /|
/  0
```


We also allow a more efficient representation by "factoring out" common subterms, e.g. terms with tree representations

\[
\begin{align*}
&\begin{array}{c}
\text{a} \\
1 \quad 2
\end{array} \\
&\begin{array}{c}
a \\
1 \quad 2 \\
a \quad b
\end{array}
\quad \quad \quad \quad
\begin{array}{c}
\text{b} \\
1 \quad 2
\end{array} \\
&\begin{array}{c}
\text{a} \\
1 \quad 2 \\
\text{a} \quad \text{b} \quad \text{b}
\end{array}
\end{align*}
\]

become, after factoring, the dag

\[
\begin{align*}
&\begin{array}{c}
\text{a} \\
1 \quad 2
\end{array} \\
&\begin{array}{c}
a \\
1 \quad 2 \\
\text{a} \quad \text{b}
\end{array}
\quad \quad \quad \quad
\begin{array}{c}
\text{b} \\
1 \quad 2
\end{array} \\
&\begin{array}{c}
\text{b} \\
1 \quad 2 \\
\text{a} \quad \text{b}
\end{array}
\end{align*}
\]

A presentation will be given by a labeled dag representing the terms appearing in $G$ and $\Gamma$, with an extra undirected edge set connecting the roots of $x$ and $y$, where $x \equiv y$ is an axiom of $\Gamma$. Let $<G,0,\Gamma>$ be a presentation. We will reuse the symbol $\Gamma$ to stand for the presentation $<G,0,\Gamma>$. We will denote the set of terms by $\tau$, and write $x \equiv y$ when the congruence of terms $x$ and $y$ follows from the axioms of $\Gamma$. We will denote by $\tau/\Gamma$, the algebra presented by $\Gamma$. 
Definition 1.2

The word problem is the set
\[ WP = \{ <\Gamma, x, y> \mid x \equiv y \}. \]

The finiteness problem is the set
\[ FIN = \{ \Gamma \mid \Gamma \text{ presents a finite algebra} \}. \]

As shown in [1], both WP and FIN are \( \leq_{\log}^m \)-complete for P.

Definition 1.3

Let \( D = \{ \theta k \mid \theta \in 0, 1 \leq k \leq \text{arity of } \theta \} \). Let \( a, b, \ldots \) represent strings in \( D^* \). \( \lambda \) will represent the null string. Strings in \( D^* \) will be used to specify the position of a subterm in a term, according to the following example: if \( x \) is the term

![Tree Diagram]

then \( y \) occurs as a subterm of \( x \) at position \( \theta 3 \theta' 1 \). We will write \( x ay \) if \( y \) occurs as a subterm of \( x \) at position \( a \).
Definition 1.4

\( x[\alpha \setminus y] \) is the term \( x \) with the subterm at position \( \alpha \) (if it exists) replaced by \( y \).

\( x[w \setminus y] \) is the term \( x \) with all occurrences of the subterm \( w \) in \( x \) replaced by \( y \).

Definition 1.5

\( x * y \) if there is an axiom \( z \equiv w \) of \( \Gamma \) and \( \alpha \) such that \( x\alpha z \) and \( y = x[\alpha \setminus w] \).

\( * \) is the reflexive transitive closure of \( * \).

The relation \( * \) constitutes a convenient proof system for congruence of terms:

Lemma 1.6

\( x * y \) iff \( x \equiv y \).

Proof

Easy induction on definition of \( \equiv \).

The following sets are of fundamental importance.

Definition 1.7

\( R = \{ \text{subterms of terms appearing in } \Gamma \} \).

\( x = \{ [x] \mid [x] \text{ is the congruence class of } x, x \epsilon R \} \).

\( \hat{R} = \{ y \mid [y] \in x \} = \{ y \mid \exists x \epsilon R \ x \equiv y \} \).

Definition 1.8

\( x \alpha z \) iff \( \exists y \ x \alpha y \) and \( y \equiv z \).
The following elementary properties are easy to prove, using the techniques of [1].

Lemma 1.9

(i) if \( s \equiv t \), say, \( ta^s \), & \( z \vdash R \), then \( y \vdash R \) & \( y^z \).

(ii) if \( x \equiv y \), \( y \equiv z \), & \( z \vdash R \), then \( x \equiv z \).

(iii) if \( x \equiv z \), \( x \equiv y \), & \( z \vdash R \), then \( y \equiv z \).

(iv) if \( x \equiv z \), & \( z \vdash R \) then \( x \vdash R \).

(v) if \( x \equiv y \), \( x \equiv z \), & \( z \vdash R \), then \( y \equiv z \).

(vi) if \( s \equiv t \), say, \( ta^s \), & \( z \vdash R \), then \( y \equiv z \).

(vii) if \( s \equiv t \), say, \( y \vdash R \), then \( s[z \setminus \alpha] \equiv t[z \setminus \alpha] \) for any \( z \).

(viii) if \( y \equiv z \), \( y \equiv z \), and \( y \equiv R \), then \( \alpha = \lambda \).

(ix) if \( 0x_1 \ldots x_m \equiv 0y_1 \ldots y_m \) and \( 0x_1 \ldots x_m \vdash R \), then \( x_1 \equiv y_1 \), \( 1 \equiv \alpha \).

Proof

We will prove (i) as an illustration of the techniques; the rest are equally straightforward and are left as exercises.

Assume \( s \equiv t \), say, \( ta^s \), & \( z \vdash R \).

In a proof \( t = t_1 + t_2 + \ldots + t_n \equiv s \) of \( t \equiv s \), if there is a minimal \( i \) such that \( t_1 + t_{i+1} \vdash t_1 \gamma w, t_{i+1} = t_i [\gamma \setminus x] \) where \( w \equiv x \) is an axiom, and \( \gamma \) is an initial substring of \( \alpha \beta \), then \( t_i \equiv s \) and \( x \) is congruent to a subterm of \( w \). But this subterm of \( w \) is in \( R \), contradicting the assumption \( z \vdash R \). Thus no such \( i \) can exist.

This says that \( s \equiv z \). But \( s \equiv y \), so \( y \equiv w \) and \( w \equiv y \), but then \( w \equiv z \), and as above, \( y \equiv z \).
To show $y \not\in \hat{R}$, note $y \not\in z$ implies $y \not\in x$ for some $x$; but if $y \in \hat{R}$ then $x \not\in \hat{R}$, contradicting the assumption that $z \not\in \hat{R}$.

\textbf{Definition 1.10}

Let $\Gamma$ be a given. Let $\mathcal{V} = (v_1, v_2, \ldots)$ be a set of variables. Let $G^+ = G \cup \mathcal{V}$, $\tau^+ = \{\text{terms over } G^+ \text{ and } 0\}$. Thus $\tau^+$ is the set of terms with occurrences of variables. A \textbf{schema} is a formula $s \in t$, $s, t \in \tau^+$. A \textbf{closed formula} is one of the form

$$O_1 v_1 \ldots O_k v_k \ s \in t$$

where each $O_i$ is either $\exists$ or $\forall$, and all variables occurring in $s$ and $t$ are among $v_1, \ldots, v_k$.

\textbf{Definition 1.11}

A closed formula $\phi$ is \textbf{true} in $\Gamma$ (denoted $\Gamma \vdash \phi$) if either

(i) $\phi$ is of the form $s \in t$ (note in this case $s, t \in \tau$ since $\phi$ is closed) and $s$ is congruent to $t$.

(ii) $\phi$ is of the form $\forall v \psi$ and for all $x \in \tau$, $\Gamma \vdash \psi[v \setminus x]$.

(iii) $\phi$ is of the form $\exists v \psi$ and there is an $x \in \tau$ such that $\Gamma \vdash \psi[v \setminus x]$.

Let $v_1, \ldots, v_k$ be the variables occurring in $s$ and $t$. We will write $\bar{x}$ for a $k$-tuple of terms in $\tau$, and $s(\bar{x})$ for $s[v_1 \setminus x_1] \ldots [v_k \setminus x_k]$. By the definition of truth above, $\Gamma \vdash O_1 v_1 \ldots O_k v_k \ s \in t$ (**) iff

$$O_1 x_1 \ldots O_k x_k \ s(\bar{x}) \equiv t(\bar{x}).$$
Note that (*) is an assertion about the truth of a sentence in some language interpreted over the domain \( \tau / \tau \) (here the \( Q_i \) are symbols in the language), while (**) is a metastatement about congruence of terms in \( \tau \) (here the \( Q_i \) represent the English "for all" and "there is" in Definition 1.11 (ii) and (iii)). This is a subtle distinction which should be recognized, but which we will find convenient to ignore in general.
2. Main Results

Definition 2.0

Let $S_n(v_n) = \{<\Gamma, Q_1v_1\ldots Q_kv_k sE\} |$

$Q_1\ldots Q_k$ is a string of quantifiers with $n$

alternations, the outermost a $\exists(V)$, and

$\Gamma \vdash Q_1v_1\ldots Q_kv_k sE t \}$.

In the following, let $\Gamma$ and $Q_1v_1\ldots Q_kv_k sE t$ be fixed.

Definition 2.1

$R^+ = \{\text{subterms of } s \text{ and } t\}$.

$R_1 = Ru(R^+ n \Gamma)$;

$r_1 = \{[x][xR_1]\}$;

$\hat{R}_1 = \{y|[y]r_1\} = \{y|\exists xR_1 x\equiv y\}$.

We wish to develop a means of describing the syntactic

interdependence of terms in $R^+$.

Definition 2.2

Let $\sim$ be defined on $(R^+)^2$ as the smallest equivalence

relation satisfying

(i) $s \sim t$

(ii) $\theta x_1\ldots x_n \sim \theta y_1\ldots y_n$

$\frac{x_1 \sim y_1, \ldots, x_n \sim y_n}{x_1 \sim y_1, \ldots, x_n \sim y_n}$

Note that (i) and (ii) plus the axioms
(iii) \( x \sim x \)

(iv) \( x \sim y \)
\[ y \sim x \]

(v) \( x \sim y, y \sim z \)
\[ x \sim z \]

constitute a complete proof system for \( \sim \).

The purpose of \( \sim \) is to determine which subterms of \( s \) & \( t \) are forced by syntax to be congruent under most interpretations of the variables.

**Lemma 2.3**

If \( s(\overline{x}) \equiv t(\overline{x}), u \sim w, \) and \( u(\overline{x}) \not\models R, \) then \( u(\overline{x}) \equiv w(\overline{x}). \)

**Proof**

Easy induction on proof of \( u \sim w, \) using Lemma 1.9.

The axioms and rules (i) - (v) above for \( \sim \) allow us to decide whether \( u \sim w \) in polynomial time. More importantly,

**Lemma 2.4**

There is a polynomial time algorithm to construct \( \sim \) on \( R^+ \).

**Proof**

Construct edges between subtrees representing terms in \( R^+ \) as in the proof of Theorem 1 of [1].

The following technical lemma establishes the relationship between \( \sim \) and the ternary relation of Definition 1.3.
Lemma 2.5

If $x \sim x'$, $x \beta y$, and $x' \beta y'$, then $y \sim y'$.

Proof

Induction on length of $\beta$. ■

At this point we introduce two essential concepts. Let $v_i$ be a variable.

Definition 2.6

$v_i$ is **immune** if any of the following hold:

(i) $\exists u \; v_i \sim u$ and $u \in R_1$ (i.e. $u$ contains no variables);

(ii) $\exists u \; v_i \sim u$ and $v_i$ is a proper subterm of $u$;

(iii) $\exists u, w$ such that $v_i$ is a proper subterm of $u$, $u \not\sim w$, and the labels at the roots of $u$ and $w$ differ. ■

Definition 2.7

$v_i$ is **principal** if there is no proper term $u$ (one not in $G$ or $V$) with $v_i \sim u$. ■

Intuitively, immunity is a sufficient condition that a variable be forced syntactically to assume a value in $r_1$ in any assignment to the variables satisfying the schema $s \models t$.

Lemma 2.8

If $v_i$ is immune and $s(\overline{x}) \models t(\overline{x})$, then $[x_i] \in r_1$. 
Proof

We consider the 3 cases of immunity separately. Suppose $s(\overline{x}) \equiv t(\overline{x})$.

(i) $u \backsim v_i \& u \not\equiv R_1$.
If $x_i \backsim \hat{R}_1$, then by Lemma 2.3, $x_i \equiv u(\overline{x}) \equiv u$, thus $[x_i] = [u] \in \hat{R}_1$.

(ii) $u \not\equiv v_i \& v_i$ is a proper subterm of $u$.
If $x_i \backsim \hat{R}_1$, then by Lemma 2.3, $x_i \equiv u(\overline{x})$ and $u(\overline{x}) \alpha x_i$ for some $\alpha \not\equiv \lambda$. But this contradicts Lemma 1.9 (viii).

(iii) $u, w, \alpha \not\equiv \lambda$ such that $u \alpha v_1$, $u \not\sim w$, and labels at the roots of $u \& w$ differ. If $x_i \backsim \hat{R}_1$, then $u(\overline{x}) \not\equiv \hat{R}$ by Lemma 1.9 (iv), hence $u(\overline{x}) \equiv w(\overline{x})$ by Lemma 2.3. But by Lemma 1.9 (v), $w(\overline{x}) \alpha x_i$, thus the root of $w$ is the same as the root of $u$, contradicting the assumption. ■

Using the algorithm of Lemma 2.4, it is very easy to decide immunity and principality for a variable $v_i$. In fact,

Lemma 2.9

There is a polynomial time algorithm to

(i) decide whether $v_i$ is immune;

(ii) decide whether $v_i$ is principal;

(iii) if neither (i) nor (ii), produce a proper tree $u$ such that $v_i \backsim u$ and $u$ contains occurrences of variables, but no occurrence of $v_i$.

Proof

Exercise.
Finally we introduce a ternary relation on $V \times D \times V$ defined inductively as follows:

**Definition 2.10**

$v_1g\gamma_k \iff (i) \exists u \ v_i \sim u \text{ and } u\gamma v_k; \text{ or}$

(ii) $\alpha = \beta\gamma \text{ and } \exists v_j \ v_1\delta v_j v_k.$

This relation is meant to represent the syntactic interdependence of the variables. Its essential properties are outlined in the following 3 lemmas:

**Lemma 2.11**

If $v_1g\gamma v_k$ and $\alpha \neq \lambda$, then $v_1$ is not principal.

**Proof**

By Definition 2.10 there must be a $v_j$, an initial substring $\beta$ of $\alpha$, $\beta \neq \lambda$, and $v_i, u_i, \ldots, v_i, u_i$ such that

$v_1 \sim u_i \lambda v_i \sim u_i \lambda v_i \sim \ldots \sim u_i \beta v_j$, i.e.

$v_1 \sim v_i \sim \ldots \sim v_i \sim u_i \beta v_j$, hence $v_1 \sim u_i \beta v_j.$

**Lemma 2.12**

If $v_1g\gamma v_k$, $s(\overline{x}) \equiv t(\overline{x})$, and $x_k \models R$, then $x_1\alpha x_k$.

**Proof**

Induction on definition of $v_1g\gamma v_k$:

**Basis**

By Lemma 2.3, $x_1 \equiv u(\overline{x}) \alpha x_k$, and the conclusion follows from Lemma 1.9 (v).
Induction step \( v_i \notin v_j \forall v_k \) and \( a = \beta \).

By the induction hypothesis, \( x_j \forall x_k \), and by Lemma 1.9 (iv), \( x_j \notin R \). Again by induction hypothesis, \( x_i \notin x_j \). The conclusion follows from Lemma 1.9 (ii).

Lemma 2.13

If \( v_i \notin v_k \) and \( v_i \notin v_j \) then \( v_j \notin v_k \).

Proof

Induction on definition of \( v_i \notin v_k \), using Lemma 2.5.

The following lemma is key to the proof of the main theorem. It asserts the "independence" of principal variables from other variables.

Lemma 2.14

Let \( v_1 \) be principal and let \( x_1, y_1 \notin \hat{R}_1 \). Let \( \bigwedge_{j=1}^\infty w_j \notin u_j \)
be a conjunction of schemata with each \( w_j \in R_1 \) (i.e. \( w_j \) contains no variables) and \( u_j \in R^+ \). Then

\[
\forall \tau \models Q_2 v_2 \ldots Q_k v_k s[v_1 \setminus x_1] \supseteq t[v_1 \setminus x_1] \land \bigwedge_{j=1}^\infty w_j \notin u_j [v_1 \setminus x_1]
\]

iff

\[
\forall \tau \models Q_2 v_2 \ldots Q_k v_k s[v_1 \setminus y_1] \supseteq t[v_1 \setminus y_1] \land \bigwedge_{j=1}^\infty w_j \notin u_j [v_1 \setminus y_1]
\]

Proof

Let \( x_1, y_1 \notin \hat{R}_1 \) and assume \( x_1 \notin y_1 \), otherwise the result is immediate. Let \( x_2, \ldots, x_k \in \tau \) be arbitrary.

For 2isk, let

\[
y_i = x_i [a_1 \setminus y_1] [a_2 \setminus y_1] \ldots [a_m \setminus y_1] \quad (2.15)
\]
where the $a_j$ are all strings $a$ such that $v_1av_1$ and $x_1ax_1$. Note that no $a_j$ is an initial substring of another $a_k$, since distinct terms congruent to $x_1$ must be incomparable with respect to the subterm relation, by Lemma 1.9 (viii); thus $y_1$ is well-defined.

$y_1$ is then just $x_1$ with some subterms congruent to $x_1$ replaced by $y_1$. The subterms replaced are determined by the dependence of $v_1$ on $v_1$.

We now claim that

$$s(x) \equiv t(x) + s(y) \equiv t(y). \quad (2.16)$$

Note $s(y)$ is just $s(x)$ with some subterms congruent to $x_1$ replaced by $y_1$, and similarly for $t(y)$. Since $s(x)ax_1$ iff $t(x)ax_1$ by Lemma 1.9 (v), it suffices to show that

(a) if $s(x)ax_1$ and $s(y)ay_1$ then $t(y)ay_1$, and

(b) if $t(x)ax_1$ and $t(y)ay_1$ then $s(y)ay_1$,

i.e. if a subterm of $s(x)$ is replaced by $y_1$ in $s(y)$, then the subterm in the corresponding position of $t(x)$ is replaced by $y_1$ in $t(y)$, and vice versa; for, it follows from several applications of Lemma 1.9 (vii) that $s(y) \equiv t(y)$. We will show (a); (b) is analogous.

Let $s(x)ax_1$ and $s(y)ay_1$. There must $v_1, \beta, \gamma$ with $\alpha = \beta \gamma, s \beta v_1, x_1 \gamma x_1, a v_1$. Since $t(x)ax_1$, one of the following three cases must hold:

(a) $\exists v_j \exists x$ is a substring of $a$ and $t \xi v_j$, 

(b) $\exists v_j \exists \forall \lambda \exists \delta v_j$, or
(c) $\exists u \exists R_1 \tau u$.

But (c) is impossible, since $x_1 \exists \hat{R}_1$, and (b) is not possible, since if it were true, and $u$ were such that $t \delta v_j \exists v_j$, then $v_j \sim u$ by Lemma 2.5, hence $v_j \exists \delta v_j$, but $v_j \exists v_1$, so by Lemma 2.13, $v_j \delta v_j$, which by Lemma 2.11 contradicts the principality of $v_1$.

This leaves (a). Then $\exists \eta \alpha = \xi \eta$ and $x_j \exists \eta x_1$.

We have

$$\alpha = \beta \eta, \ s \beta \exists \eta, \ v_1 \exists \eta, \ \xi \eta, \ t \xi \exists \eta, \ x_j \exists \eta x_1.$$ 

If $\beta$ is a substring of $\xi$, let $\xi = \beta \delta$. Then $\gamma = \delta \eta$, and $v_1 \exists \delta v_j$ and $s \beta \exists \eta$, so $v_1 \exists \delta v_j$ by Lemma 2.5, thus $v_1 \exists \delta v_1$ by Lemma 2.13.

If $\xi$ is a substring of $\beta$, let $\beta = \xi \delta$. Then $\eta = \delta \gamma$, and $s \delta \exists \gamma$ and $s \xi \exists \eta$, so $v_1 \exists \delta v_1$ by Lemma 2.5, thus $v_1 \exists \delta v_1$.

Thus in either case we have $y_j \exists \gamma_1$, hence $t(y) \exists \gamma_1$, as was to be shown, and claim (2.16) is verified.

Note also that

$$w_j \equiv u_j(\overline{x}) + w_j \equiv u_j(\overline{y}),$$

since if $u_j(\overline{x}) \neq u_j(\overline{y})$ then both contain subterms not in $R_1$, hence both $w_j \equiv u_j(\overline{x})$ and $w_j \equiv u_j(\overline{y})$ are false, by Lemma 1.9 (iv) & (v).

Let $\phi$ be the formula

$$s \equiv t \land \bigwedge_{j=1}^{n} w_j \equiv u_j.$$ 

Proceeding by induction on quantifiers, assume that for all terms $x_2, \ldots, x_2$, 

\[ Q_l+1 x_{l+1} \cdots Q_k x_k \ \oplus (x_1, x_2, \ldots, x_l, x_{l+1}, \ldots, x_k) \]
\[ + Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (y_1, y_2, \ldots, y_{l-1}, x_{l+1}, \ldots, x_k), \]

where \( y_2, \ldots, y_{l-1} \) are defined by (2.15). For any fixed \( x_2, \ldots, x_{l-1} \), the existence of some \( x_l \) satisfying

\[ Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (x_1, x_2, \ldots, x_l, \ldots, x_k) \]

implies the existence of a \( z \) satisfying

\[ Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (y_1, y_2, \ldots, y_{l-1}, x_{l+1}, \ldots, x_k), \]

namely \( z = y_l \). Therefore

\[ 2x_l Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (x_1, \ldots, x_k) \]
\[ + 2x_l Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (y_1, \ldots, y_{l-1}, x_{l+1}, \ldots, x_k). \]

For any fixed \( x_2, \ldots, x_{l-1} \),

if \( \omega_l Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (x) \), then since \( x_l \in \mathbb{R}_1 \), \( \gamma_l \) is infinite (see Lemma 9 of [1]), and since for any \( a \), an \( x_a \) can be constructed such that not \( x_a < x_1 \), by Lemma 2.12 it follows that not \( x_l = x_1 \). Thus \( y_l = x_l \). But then

\[ \omega_l Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (x_1, x_2, \ldots, x_l, \ldots, x_k) \]
\[ + \omega_l Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (y_1, y_2, \ldots, y_{l-1}, x_{l+1}, \ldots, x_k) \]
\[ + \omega_l Q_{l+1} x_{l+1} \cdots Q_k x_k \ \oplus (y_1, \ldots, y_{l-1}, x_{l+1}, x_l, x_{l+1}, \ldots, x_k). \]

We have shown by induction that

\[ Q_2 x_2 \cdots Q_k x_k \ \oplus (x_1, x_2, \ldots, x_k) \]
\[ + Q_2 x_2 \cdots Q_k x_k \ \oplus (y_1, x_2, \ldots, x_k), \]

and the converse follows from symmetry. \( \square \)

Parallel algorithms were introduced in [3,5]. It was shown in [3,5] that parallel polynomial time computations accept exactly the sets in PSPACE, and in [3] that such
computations restricted to $n$ alternations of $\land$- and $\lor$-branches, starting with an $\lor$-branch ($\land$-branch), accept exactly the sets in $\Sigma_n^P \cap \Pi_n^P$, where $\Sigma_n^P \cap \Pi_n^P$ is the $n$th $\Sigma$ ($\Pi$) level of the polynomial time hierarchy [2]. Here we apply such a computation to the closed formula

$$Q_1 v_1 \ldots Q_k v_k \equiv t,$$

using $\land$-branching to eliminate $\forall$ quantifiers, and $\lor$-branching to eliminate $\exists$ quantifiers.

**Theorem 2.17**

There is a parallel polynomial time algorithm to decide, given $\Gamma$ and $Q_1 v_1 \ldots Q_k v_k \equiv t$, whether

$$\forall \tau/\Gamma : Q_1 v_1 \ldots Q_k v_k \equiv t.$$

**Proof**

Let $w_j \equiv y_j$, $1 \leq j \leq l$, be a set of schemata, $w_j \in R_1$, $y_j \in R^+$. The schemata $w_j \equiv y_j$ may be represented by an extra undirected edge set on the dag representing $\equiv t$ and $\Gamma$. We show how to decide truth of formulas of the form

$$Q_1 x_1 \ldots Q_k x_k \{s(\bar{x}) \equiv t(\bar{x}) \lor \bigwedge_{j=1}^l w_j \equiv y_j(\bar{x})\}. \quad (2.18)$$

On input $\Gamma$ and (2.18), run the word problem algorithm of Theorem 1 of [1] to determine all congruent pairs of terms in $R_1$, and run the finiteness algorithm of Theorem 12 of [1] to determine if $\forall \tau/\Gamma$ is finite. Use the algorithm of Lemma 2.9 to determine immunity and principality of variables.
Suppose \( Q_1 = V \). Then
\[
\forall x_1, Q_2 x_2 \ldots Q_k x_k \left[ s(\bar{x}) \equiv t(\bar{x}) \land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}) \right]
\]
iff
\[
\forall x_1 \in R_1 \ u_1 + Q_2 x_2 \ldots Q_k x_k \left[ s(\bar{x}) \equiv t(\bar{x}) \land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}) \right]
\]
\[\& \ \forall x_1 \in R_1 \ u_1 + Q_2 x_2 \ldots Q_k x_k \left[ s(\bar{x}) \equiv t(\bar{x}) \land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}) \right]\]
iff
\[
\bigwedge_{x_1 \in R_1} Q_2 x_2 \ldots Q_k x_k \left[ s(\bar{x}) \equiv t(\bar{x}) \land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}) \right] \tag{2.19}
\]
\[\& \ \forall x_1 \in R_1 \ u_1 + Q_2 x_2 \ldots Q_k x_k \left[ s(\bar{x}) \equiv t(\bar{x}) \land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}) \right]. \tag{2.20}
\]

At this point in the algorithm a series of \( \wedge \)-branches is made, spawning \( n+1 \) independent parallel processes, where \( n \) is the cardinality of \( R_1 \). The first \( n \) processes will each pick a different \( x_1 \in R_1 \) and verify one clause of (2.19), by calling the algorithm recursively with input
\[
\langle \Gamma, Q_2 v_2 \ldots Q_k v_k \left[ s[v_1 \backslash x_1] \equiv t[v_1 \backslash x_1] \land \bigwedge_{j=1}^k w_j \equiv y_j(v_1 \backslash x_1) \right] \rangle.
\]
The size of the problem is not increased, since consolidation of common subterms is allowed; occurrences of \( v_1 \) in the representation of \( s, t, \) and \( y_j \) may be replaced with pointers to \( x_1 \).

The remaining process will verify (2.20). If \( \tau/\tau \) is finite, then the process may immediately accept, since by Theorem 9 of [1], \( r_1 = \tau/\tau \), hence (2.20) holds vacuously. Suppose then that \( \tau/\tau \) is infinite. If \( v_1 \) is immune, then the process may immediately reject, since by Lemma 2.8, there is no satisfying assignment with \([x_1] r_1 \).
If \( v_1 \) appears in any of the \( y_j \), then the process may immediately reject, by Lemma 1.9 (iv) and (v). If \( v_1 \) is not immune and does not appear in any \( y_j \), but \( v_1 \) is principal, then by Lemma 2.14, (2.20) holds iff
\[
O_2x_2\ldots O_kx_k \ [s(x^*,x_2,\ldots,x_k) \equiv t(x^*,x_2,\ldots,x_k) \land \bigwedge_{j=1}^k w_j \equiv y_j(x)] \quad (2.21)
\]
where \( x^* \) is any term not in \( R_1 \). In polynomial time, the process may find such an \( x^* \) by locating an \( m \)-ary \( t \) and terms \( u_1,\ldots,u_m \in R \) such that \( \theta u_1\ldots u_m \hat{\in} R \). The algorithm is exactly the one used to decide finiteness (see [1], Theorem 12). The word problem algorithm may be run to determine if \( \theta u_1\ldots u_m \equiv x \) for some \( x \in R_1 \); if not, take \( x^* = \theta u_1\ldots u_m \); if so, let \( u \) be the largest term in \( R_1 \) containing \( x \) as a subterm and take \( x^* = \theta u \ldots u \). It is easily verified that \( x^* \hat{\in} R_1 \), but all proper subterms \( x^* \) are in \( R_1 \).

Now the process determines whether (2.21) holds, by calling the algorithm recursively with input:
\[
<\Gamma, O_2v_2\ldots O_kv_k \ [s[v_1\setminus x^*] \equiv t[v_1\setminus x^*] \land \bigwedge_{j=1}^k w_j \equiv y_j]>.
\]
As before, the size of the problem is not increased; we may replace each occurrence of \( v_1 \) in the dag representing \( s \) and \( t \) with the label \( \theta \) and edges to each of the immediate subterms of \( x^* \), which all lie in \( R_1 \).

Finally, if \( v_1 \) is neither immune nor principal, then Lemma 2.9 guarantees us a \( u \in R^+ \) such that \( v_1 - u, u \) is a proper tree containing occurrences of variables, and \( v_1 \) does not occur in \( u \). Then by Lemma 2.3, (2.20) is equivalent to
\[ \forall x_1 \, \exists R_1 \, \forall x_2 \ldots \forall x_k \, [s(\overline{x}) = s(\overline{x}) \land \bigwedge_{j=1}^{k} w_j = y_j(\overline{x}) \land x_1 = u(\overline{x})], \quad (2.22) \]

and since \( x_1 = u(\overline{x}) \) implies \( s[v_1 \setminus u](\overline{x}) = s(\overline{x}) \) and \( t[v_1 \setminus u](\overline{x}) = t(\overline{x}) \),

(2.22) is equivalent to

\[ \forall x_1 \, \exists R_1 \, \forall x_2 \ldots \forall x_k \, [s[v_1 \setminus u](\overline{x}) = s[v_1 \setminus u](\overline{x}) \land \bigwedge_{j=1}^{k} w_j = y_j(\overline{x}) \land x_1 = u(\overline{x})]. \quad (2.23) \]

Note that schema \( s[v_1 \setminus u] = t[v_1 \setminus u] \) may be represented as concisely as \( s = t \), by replacing occurrences of \( v_1 \) with pointers to \( u \). Since \( u \) contains no occurrences of \( v_1 \), the graph remains a dag.

At this point the process may reject immediately if there is more than one operator symbol in \( \Theta \); otherwise there would certainly be an \( x_1 \, \exists R_1 \) with its root symbol differing from that of \( u \), thus \( x_1 \notin u(\overline{x}) \) for any \( \overline{x} \) by Lemma 1.9 (v). Hence assume \( \Theta \) is the only operator symbol, and let \( \Theta \) be \( m \)-ary.

The process may reject immediately if \( uab \) and \( bG \), since if \( y \) is any term not in \( \hat{R} \) and \( x_1ay \), then \( x_1 \hat{R} \) and \( x_1 \notin u(\overline{x}) \) by Lemma 1.9 (iv), (v). Therefore we may assume all leaves of \( u \) are variables.

Finally, the process may reject immediately if \( uav_1, u\beta v_1 \), and \( \alpha \neq \beta \), since if \( y_1, \beta y_2 \hat{R}, y_1 \notin y_2, x_1 ay_1, x_1 \beta y_2 \), then \( x_1 \hat{R} \) and \( x_1 \notin u(\overline{x}) \), as above. \( y_1 \) and \( y_2 \) exist, since we have assumed \( \tau / r \) infinite. Thus we may assume that each leaf of \( u \) is labeled with a different variable name. This says that no two subterms of \( u \) are identical, hence the physical representation of the term \( u \) is a tree, not just a dag. This observation will be instrumental in achieving a good time analysis below.
Now, since \( u \) is a proper tree, say \( u = u_1 \ldots u_m \), and since every element of \( G \) is in \( R_1 \), (2.23) is equivalent to
\[
\forall x_{11}^{\hat{R}_1} \forall x_{12} \ldots \forall x_{1m} \left( \theta x_{11} \ldots x_{1m} \mid R_1 + Q_{x_2} \ldots Q_{x_k} [s[v_1 \backslash u](\overline{x}) \equiv t[v_1 \backslash u](\overline{x}) \land \bigwedge_{j=1}^{m} w_j \equiv y_j(\overline{x}) \land \theta x_{11} \ldots x_{1m} \equiv \theta u_1(\overline{x}) \ldots u_m(\overline{x})] \right),
\]
which by Lemma 1.9 (ix) is equivalent to
\[
\forall x_{11}^{\hat{R}_1} \forall x_{12} \ldots \forall x_{1m} \left( \theta x_{11} \ldots x_{1m} \mid R_1 + Q_{x_2} \ldots Q_{x_k} [s[v_1 \backslash u](\overline{x}) \equiv t[v_1 \backslash u](\overline{x}) \land \bigwedge_{j=1}^{m} w_j \equiv y_j(\overline{x}) \land \bigwedge_{j=1}^{m} x_{1j} \equiv u_j(\overline{x})] \right),
\]
which in turn is equivalent to
\[
\exists x_{11}^{\hat{R}_1} (\forall x_{12} \ldots \forall x_{1m} \left( \theta x_{11} \ldots x_{1m} \mid R_1 + Q_{x_2} \ldots Q_{x_k} [s[v_1 \backslash u](\overline{x}) \equiv t[v_1 \backslash u](\overline{x}) \land \bigwedge_{j=1}^{m} w_j \equiv y_j(\overline{x}) \land \bigwedge_{j=1}^{m} x_{1j} \equiv u_j(\overline{x})] \right),
\]
(2.25)
and as above, the process \( \land \)-branches into \( n+1 \) processes, the first \( n \) of which each verify a clause of (2.25) for some \( x_{11} \in \hat{R}_1 \), and the remaining process verifies (2.26). Since \( x_{11} \in \hat{R}_1 \), and the remaining process verifies (2.26). Since
\[
\forall x_{12} \ldots \forall x_{1m} \left( \theta x_{11} \ldots x_{1m} \mid R_1 + Q_{x_2} \ldots Q_{x_k} [s[v_1 \backslash u](\overline{x}) \equiv t[v_1 \backslash u](\overline{x}) \land \bigwedge_{j=1}^{m} w_j \equiv y_j(\overline{x}) \land \bigwedge_{j=1}^{m} x_{1j} \equiv u_j(\overline{x})] \right),
\]
(2.26)
and as above, the process \( \land \)-branches into \( n+1 \) processes, the first \( n \) of which each verify a clause of (2.25) for some \( x_{11} \in \hat{R}_1 \), and the remaining process verifies (2.26). Since
\[
\forall x_{12} \ldots \forall x_{1m} \left( \theta x_{11} \ldots x_{1m} \mid R_1 + Q_{x_2} \ldots Q_{x_k} [s[v_1 \backslash u](\overline{x}) \equiv t[v_1 \backslash u](\overline{x}) \land \bigwedge_{j=1}^{m} w_j \equiv y_j(\overline{x}) \land \bigwedge_{j=1}^{m} x_{1j} \equiv u_j(\overline{x})] \right),
\]
(2.27)
Now each process attempting to verify a clause of (2.25) for some \( x_{11} \in \hat{R}_1 \) may take \( v_{k+1} = x_{11}, y_{k+1} = u_1 \), and verify that
∀x_{12}...∀x_{1m} ∃x_{11}...x_{1m} \{ R_1 + \\
Q_2x_2...Q_kx_k \{ s[v_1\setminus u](x) ≜ t[v_1\setminus u](x) \\
\land \bigwedge_{j=1}^{l+1} w_j ≜ y_j(x) \land \bigwedge_{j=l+2}^{m} x_{1j} ≜ u_j(x) \}
\}

by attacking x_{12} in the same way x_{11} was attacked in (2.24).

Eventually, there are some processes attempting to verify

\[ \exists x_{11}...x_{1m} \{ R_1 + \\
Q_2x_2...Q_kx_k \{ s[v_1\setminus u](x) ≜ t[v_1\setminus u](x) \\
\land \bigwedge_{j=1}^{l} w_j ≜ y_j(x) \land \bigwedge_{j=1}^{m} x_{1j} ≜ u_j(x) \}
\]

with x_{11},...x_{1m} ∈ R_1. The process may use the word problem algorithm to dispose of the antecedent.

As for the process verifying (2.27), if u is a proper tree, x_{11} and u are broken up in the same way x_1 and u were in (2.23). This procedure continues until all subterms of u have been broken up. Since variables reside at the leaves of u, we are left with formulas of the form

\[ \forall x_{11} \{ R_1...\forall x_{1j} \{ R_1 O_2x_2...Q_kx_k \{ s[v_1\setminus u](x) ≜ t[v_1\setminus u](x) \\
\land \bigwedge_{j=1}^{l} w_j ≜ y_j(x) \land \bigwedge_{j=1}^{m} x_{1j} ≜ u_j(x) \}
\}
\]

(2.28)

It follows from the fact that the size of u was no bigger than the size of its physical representation that the above was a polynomial time \( \wedge \)-computation. Moreover, since no two subterms of u were identical, each \( x_i \) occurs among the \( x_{ij} \) at most once. If some \( x_{ij} \) is universally quantified, then the process can immediately reject, since (2.28) would imply \( \forall x_{ij} \forall x_{ij} x_{ij} ≜ x_{ij} \), which is false in any infinite (or for that matter,
any nontrivial) structure.

Let $\bar{x}'$ be $\bar{x}$ with each $x_{i_j}$ replaced by $z_{i_j}$. Since $z_{i_j} \equiv x_{i_j}$ is in conjunction with the rest of the formula, (2.28) is equivalent to

$$\forall s_1 \forall \hat{R}_1 \ldots \forall s_n \forall \hat{R}_1 \hat{R}_2 \ldots \hat{R}_k [s[v_1 \cup u](\bar{x}') \equiv [v_1 \cup u](\bar{x}')$$

$$\land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}') \land \bigwedge_{j=1}^k z_{i_j} \equiv x_{i_j}].$$

(2.29)

But now, since each $x_{i_j}$ occurs only in the atomic formula $z_{i_j} \equiv x_{i_j}$ and each $x_{i_j}$ is existentially quantified, (2.29) is equivalent to

$$\forall s_1 \forall \hat{R}_1 \ldots \forall s_n \forall \hat{R}_1 \hat{R}_2 \ldots \hat{R}_k [s[v_1 \cup u](\bar{x}') \equiv [v_1 \cup u](\bar{x}')$$

$$\land \bigwedge_{j=1}^k w_j \equiv y_j(\bar{x}')]$$

(2.30)

where $Q_1 x_2 \ldots Q_k x_k'$, is $Q_2 x_2 \ldots Q_k x_k$ with all the $S_{x_{i_j}}$ removed.

(2.30) is similar to (2.18), with the exception that some quantifiers are bounded (this constitutes no problem, as the reader may easily verify). The new string of quantifiers has one less quantifier than the old string, and has no more alternations than that of (2.18); and if the new string begins with an $Q$, it has fewer. Moreover, the physical representation of (2.30) is no bigger than that of (2.18). Thus the algorithm may be reapplied to (2.30).

Eliminating a leading $S$ is similar in most respects, and we leave this case as an exercise.

Finally, when all quantifiers have been eliminated, we are left with a formula
\[ \bigcup_{j=1}^{l} w_j \S u_j \quad w_j \S u_j \S r \]

which can be solved by the word problem algorithm of Theorem 1 of [1].

**Theorem 2.31**

\[ S_n (V_n) \text{ is }^{\leq \log} \text{-complete for } \mathcal{L}_n^P (\Pi^P_n), \text{ and } \bigcup_{n=0}^{\infty} S_n uV_n \]

is \( ^{\leq \log} \) -complete for PSPACE.

**Proof**

That \( S_n (V_n) \text{ is in } \mathcal{L}_n^P (\Pi^P_n) \) follows the observation that executing the algorithm of Theorem 2.17 on an input in \( S_n (V_n) \) results in a \( \Pi^P_n \) computation [3], that \( \bigcup_{n=0}^{\infty} S_n uV_n \) is in PSPACE follows from the fact that \( /\!/ \text{PTIME} = \text{PSPACE} \) [3], and \( \bigcup_{n=0}^{\infty} S_n uV_n \) is in \( /\!/ \text{PTIME} \) by the algorithm of Theorem 2.17.

To show these problems are hard for their respective classes, there are trivial reductions from the corresponding sets of quantified Boolean expressions, shown in [2] to be complete, to \( S_n \) and \( V_n \), by taking \( \Gamma \) to present the two-element Boolean algebra, as in Example 1.1.
3. Directions for Further Research

The proofs in the preceding section are far from elegant. It would perhaps be instructive to exploit the relationship between finitely presented algebras and the finite tree automata of Thatcher and Wright [4] and others, to smooth things out a bit. It is conjectured that, given schema \( s \equiv t \) and \( \Gamma \), the set

\[
\{ (x_1, \ldots, x_k) \mid s(x_1, \ldots, x_k) \equiv t(x_1, \ldots, x_k) \}
\]

is a regular set of \( k \)-tuples of trees.

If the above is the case, what can be said if we limit our attention to monadic operators? Trees become strings in this case, and it is known that the membership problem for regular sets is complete for deterministic logspace and the emptiness problem is complete for nondeterministic logspace. Do these results generalize to an analog of Theorem 2.31 for the logspace hierarchy in the monadic case?

Finally, what is the import of Theorem 2.31 with respect to first order logic with equality? Can Theorem 2.17 be extended easily to include atomic formulas \( s \equiv t \) connected by the Boolean connectives \( \land, \lor \)? The conjecture is yes, based on the fact that first order predicate logic with equality but without negation is NP-complete [6].
References


