Decidability and Complexity of Simultaneous Rigid E-Unification with One Variable and Related Results

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Abstract. We show that simultaneous rigid E-unification, or SREU for short, is decidable and in fact EXPTIME-complete in the case of one variable. This result implies that the $\forall^*\exists\forall^*$ fragment of intuitionistic logic with equality is decidable. Together with a previous result regarding the undecidability of the $\exists\exists$-fragment, we obtain *a complete classification of decidability of the prenex fragment of intuitionistic logic with equality, in terms of the quantifier prefix.* It is also proved that SREU with one variable and a constant bound on the number of rigid equations is P-complete. Moreover, we consider a case of SREU where one allows several variables, but each rigid equation either contains one variable, or has a ground left-hand side and an equality between two variables as a right-hand side. We show that SREU is decidable also in this restricted case.

Keywords : rigid E-unification, finite tree automata, logic with equality

1 Introduction

In Gallier, Raatz and Snyder [25] and Degtyarev, Gurevich and Voronkov [12], it is explained why simultaneous rigid E-unification, or SREU for short, plays such a fundamental role in automatic proof methods in classical logic with equality that are based on the Herbrand theorem, like semantic tableaux [21], the connection method [2] or the mating method [1], model elimination [37], and others.

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It was shown recently in Degtyarev and Voronkov [15] that SREU is undecidable. The strong connections between SREU and intuitionistic logic with equality have led to new important decidability results in the latter area [16,54]. It follows, for example, that the $\exists^*$-fragment of intuitionistic logic with equality is undecidable [17,18]. This result is improved in Veanes [51] to the following.

The $\exists\exists$-fragment of intuitionistic logic with equality is undecidable.

The decidability of the $\exists$-fragment of intuitionistic logic with equality, or equivalently SREU with one variable, has been an open problem which is settled in this paper. We prove the following.

SREU with one variable is decidable, in fact EXPTIME-complete.

This result is obtained by a polynomial time reduction of SREU with one variable to the intersection nonemptiness problem of finite tree automata. The latter problem is EXPTIME-complete [50]. By using an analogue of a Skolemization result for intuitionistic logic [16] we can deduce the following result.

The $\forall^*\exists\forall^*$-fragment of intuitionistic logic with equality is decidable.

The above results imply the following main contribution of this paper.

A complete classification of decidability of the prenex fragment of intuitionistic logic with equality, in terms of the quantifier prefix.

We prove also that rigid E-unification with one variable is P-complete and that SREU with one variable and a constant bound on the number of rigid equations is P-complete. One conclusion we can draw from this is that the intractability of SREU with one variable is strongly related to the *number* of rigid equations and not their *size*. With *two* variables, SREU is undecidable already with *three* rigid equations [29].

Moreover, we consider a case of SREU where one allows several variables, but each rigid equation either contains one variable, or has a ground left-hand side and an equality between two variables as a right-hand side. We show that SREU is decidable also in this restricted case. The proof is by reduction to the decidable first-order theory of ground rewrite systems, or GRS [10].

In Section 7 we summarize the current status of SREU and list some open problems.

2 Preliminaries

We will first establish some notation and terminology. We follow Chang and Keisler [4] regarding first-order languages and structures. For the purposes of this paper it is enough to assume that the first-order languages that we are dealing with are languages with equality and contain only function symbols and constants, so we will assume that from here on. We will in general use Σ, possibly with an index, to stand for a signature, i.e., Σ is a collection of function symbols with fixed arities. A function symbol of arity 0 is called a *constant*. We will always assume that *Σ contains at least one constant.*

2.1 Terms and Formulas

Terms and formulas are defined in the standard manner. We refer to terms and formulas collectively as *expressions*. In the following let X be an expression or a set of expressions or a sequence of such.

We write $\Sigma(X)$ for the *signature of* X, i.e., the set of all function symbols that occur in X, $\mathcal{V}(X)$ for the set of all free variables in X. We write $X(x_1, x_2, \ldots, x_n)$ to express that $\mathcal{V}(X) \subseteq \{x_1, x_2, \ldots, x_n\}$. Let $t_1, t_2, \ldots, t_n$ be terms, then $X(t_1, t_2, \ldots, t_n)$ denotes the result of replacing each (free) occurrence of x_i in X by t_i for $1 \leq i \leq n$. By a *substitution* we mean a function from variables to terms. We will use θ to denote substitutions. We write $X\theta$ for $X(\theta(x_1), \theta(x_2), \ldots, \theta(x_n))$.

We say that X is *closed* or *ground* if $\mathcal{V}(X) = \emptyset$. By $\mathcal{T}_\Sigma$ or simply $\mathcal{T}$ we denote the set of all ground terms over the signature Σ. A substitution is called *ground* if its range consists of ground terms. A closed formula is called a *sentence*. Since there are no relation symbols all the atomic formulas are *equations*, i.e., of the form $t \approx s$ where t and s are terms and '$\approx$' is the formal equality sign.

2.2 First-Order Structures

First-order structures will (in general) be denoted by upper case Gothic letters like $\mathfrak{A}$ and $\mathfrak{B}$ and their domains by corresponding capital Roman letters like A and B respectively. A first-order structure in a signature Σ is called a Σ-*structure*. For $F \in \Sigma$ we write $F^{\mathfrak{A}}$ for the interpretation of F in $\mathfrak{A}$.

For X a sentence or a set of sentences, $\mathfrak{A} \models X$ means that the structure $\mathfrak{A}$ is a *model of* or *satisfies* X according to Tarski's truth definition. A set of sentences is called *satisfiable* if it has a model. If X and Y are (sets of) sentences then $X \models Y$ means that Y is a *logical consequence* of X, i.e., that every model of X is a model of Y. We write $X \equiv Y$ when $X \models Y$ and $Y \models X$. We write $\models X$ to say that X is *valid*, i.e., true in all models.

By the *free algebra over* Σ we mean the Σ-structure $\mathfrak{A}$, with domain $\mathcal{T}_\Sigma$, such that for each n-ary function symbol $f \in \Sigma$ and $t_1, \ldots, t_n \in \mathcal{T}_\Sigma$, $f^{\mathfrak{A}}(t_1, \ldots, t_n) = f(t_1, \ldots, t_n)$. We let $\mathcal{T}_\Sigma$ also stand for the free algebra over Σ.

Let E be a set of ground equations. Define the equivalence relation $=_E$ on $\mathcal{T}$ by $s =_E t$ if and only if $E \models s \approx t$. By $\mathcal{T}_{\Sigma/E}$ (or simply $\mathcal{T}_{/E}$) we denote the quotient of $\mathcal{T}_\Sigma$ over $=_E$. Thus, for all $s, t \in \mathcal{T}$,

$$\mathcal{T}_{/E} \models s \approx t \quad \Leftrightarrow \quad E \models s \approx t.$$

We call $\mathcal{T}_{/E}$ the *canonical model* of E. Structures that are isomorphic with the canonical model of a finite set of ground equations are sometimes called *finitely presented algebras*. Various problems that are related to finitely presented algebras, and their computational complexity, have been studied in Kozen [31,32]. Below, we will make use of some of those results.

2.3 Simultaneous Rigid *E*-Unification

A *rigid equation* is an expression of the form $E \models_{\forall} s \approx t$ where E is a finite set of equations, called the *left-hand side* of the rigid equation, and s and t are arbitrary terms. A *system* of rigid equations is a finite set of rigid equations. A substitution θ is a *solution of* or *solves* a rigid equation $E \models_{\forall} s \approx t$ if

$$\models \quad (\bigwedge_{e \in E} e\theta) \Rightarrow s\theta \approx t\theta,$$

and θ is a *solution of* or *solves* a system of rigid equations if it solves each member of that system. The problem of solvability of systems of rigid equations is called *simultaneous rigid E-unification* or SREU for short. Solvability of a single rigid equation is called *rigid E-unification*. Rigid E-unification is known to be decidable, in fact NP-complete [24].

2.4 Term Rewriting

In some cases it is convenient to consider a system of ground equations as a rewrite system. We will assume that the reader is familiar with basic notions regarding ground term rewrite systems [19]. We will only use very elementary properties. In particular, we will use the following property of canonical (or convergent) rewrite systems. Let R be a ground and canonical rewrite system and consider it also as a set of equations. For any ground term t, let $t{\downarrow_R}$ denote the normal form of t with respect to R. Then, for all ground terms t and s, (cf [19, Section 2.4])

$$R \models t \approx s \quad \Leftrightarrow \quad t{\downarrow_R} = s{\downarrow_R}.$$

A *reduced* set of rules R is such that for each rule $l \to r$ in R, l is irreducible with respect to $R \setminus \{l \to r\}$ and r is irreducible with respect to R. In the case of ground rules, a reduced set of rules is also canonical [46]. It is always possible to find a reduced set of ground rewrite rules that is equivalent to a given finite set of ground equations [35]. Moreover, this can be done in $O(n \log n)$ time [46].

2.5 Finite Tree Automata

Finite tree automata, or simply tree automata from here on, is a generalization of classical automata. Tree automata were introduced, independently, in Doner [20] and Thatcher and Wright [48]. The main motivation was to obtain decidability results for the weak monadic second-order logic of the binary tree. Here we adopt the following definition of tree automata, that is based on rewrite rules [5,7].

► A *tree automaton* or *TA* A is a quadruple (Q, Σ, R, F) where
- Q is a finite set of constants called *states*,
- Σ is a *signature* that is disjoint from Q,
- R is a set of *rules* of the form $f(q_1, \ldots, q_n) \to q$, where $f \in \Sigma$ has arity $n \geq 0$ and $q, q_1, \ldots, q_n \in Q$,

- $F \subseteq Q$ is the set of *final states*.

A is called a *deterministic* TA or DTA if there are no two different rules in R with the same left-hand side.

Note that if A is deterministic then R is a reduced set of ground rewrite rules and thus canonical [46]. Tree automata as defined above are usually also called *bottom-up* tree automata. Acceptance for tree automata or recognizability is defined as follows.

▶ The set of terms *recognized* by a TA $A = (Q, \Sigma, R, F)$ is the set

$$T(A) = \{ \tau \in \mathcal{T}_\Sigma \mid (\exists q \in F)\ \tau \xrightarrow{*}_R q \}.$$

A set of terms is called *recognizable* if it is recognized by some TA.

Two tree automata are *equivalent* if they recognize the same set of terms. It is well known that the nondeterministic and the deterministic versions of TAs have the same expressive power [20,26,48], i.e., for any TA there is an equivalent DTA. For an overview of the notion of recognizability in general algebraic structures see Courcelle [6] and the fundamental paper by Mezei and Wright [39].

3 Decidability of SREU with One Variable

In this section we will formally establish the decidability of SREU with one variable. The proof has two parts.

1. First we prove that rigid E-unification with one variable can be reduced to the problem of testing membership in a finite union of congruence classes.
2. By using the property that any finite union of congruence classes is recognizable, we then reduce SREU with one variable to the intersection nonemptiness problem of finite tree automata.

The decidability of SREU with one variable follows then from the fact that recognizable sets are closed under boolean operations and that the nonemptiness problem of finite tree automata is decidable. In Section 4 we will address the computational complexity of this reduction.

3.1 Reduction to Membership in a Union of Congruence Classes

We start by proving two lemmas. Roughly, these lemmas allow us to reduce an arbitrary rigid equation $S(x)$ with one variable to a finite collection of rigid equations $\{ S_i(x) \mid i < n \}$ such that, for all substitutions θ, θ solves S if and only if θ solves some S_i. Furthermore, each of the S_i's has the form $E \models_\forall x = t_i$ where E is ground and t_i is some ground term. The set E is common to all the S_i's.

Let E be a set of ground equations and t a ground term. We denote by $[t]_E$ the interpretation of t in $\mathcal{T}_{/E}$, in other words $[t]_E$ is the congruence class induced by $=_E$ on $\mathcal{T}$ that includes t. For a set T of ground terms we will write $[T]_E$ for $\{ [t]_E \mid t \in T \}$. We write *Terms*(E) for the set of all terms that occur in E, in particular *Terms*(E) is closed under the subterm relation. We will use the following lemma. Lemma 1 follows also from a more general statement in de Kogel [11, Theorem 5.11].

Lemma 1. *Let t be a ground term, c a constant, E a finite set of ground equations and e a ground equation. Let $T = \mathit{Terms}(E \cup \{e\})$. If $[t]_E \notin [T]_E$ and $E \cup \{t \approx c\} \models e$ then $E \models e$.*

Proof. Assume that $[t]_E \notin [T]_E$ and that $E \cup \{t \approx c\} \models e$. Let E' be a reduced set of rules equivalent to E, such that $c{\downarrow_{E'}} = c$. Let $t' = t{\downarrow_{E'}}$. If $t' = c$ then

$$E \cup \{t \approx c\} \equiv E' \cup \{t \approx c\} \equiv E' \cup \{t' \approx c\} \equiv E$$

and the statement follows immediately. So assume that $t' \neq c$. Let $R = E' \cup \{t' \to c\}$. Let $l \to r$ be a rule in E'. Neither l nor r can be reduced with the rule $t' \to c$ because $[t']_E = [t]_E \notin [T]_E$. Hence R is reduced, and thus canonical [46]. Also, $R \equiv E \cup \{t \approx c\}$. (Note that $t' \in [t]_E$ and $[T]_E = [T]_{E'}$.)

Let $e = t_0 \approx s_0$ and let $u = t_0{\downarrow_R} = s_0{\downarrow_R}$. We have that

$$t_0 \xrightarrow{*}_R u, \quad s_0 \xrightarrow{*}_R u.$$

Consider the reduction $t_0 \xrightarrow{*}_R u$ and let $t_i \longrightarrow t_{i+1}$ be any rewrite step in that reduction. Obviously, if each subterm of t_i is in some congruence class in $[T]_E$ then the rule $t' \to c$ is not applicable since $[t']_E \notin [T]_E$ and it follows also that each subterm of t_{i+1} is in some congruence class in $[T]_E$. It follows by induction on i that the rule $t' \to c$ is not used in the reduction. The same argument holds for $s_0 \xrightarrow{*}_R u$. Hence

$$t_0 \xrightarrow{*}_{E'} u, \quad s_0 \xrightarrow{*}_{E'} u,$$

and thus $E' \models t_0 \approx s_0$. Hence $E \models e$. □

Consider a system S of rigid equations. There is an extreme case of rigid equations that are easy to handle from the point of view of solvability of S, namely the redundant ones:

- ▶ A rigid equation is *redundant* if all substitutions solve it.

To decide if a rigid equation $E(x) \models_\forall s(x) \approx t(x)$ is redundant, it is enough to decide if $E(c) \models s(c) \approx t(c)$ where c is a new constant.

- ▶ The *uniform word problem for ground equations* is the following decision problem. Given a set of ground equations E and a ground equation e, is e a logical consequence of E?

We will use the following complexity result [31,32].

Theorem 2 (Kozen). *The uniform word problem for ground equations is P-complete.*

So redundancy of rigid equations is decidable in polynomial time.

Lemma 3. *Let $E(x) \vDash_\forall e(x)$ be a rigid equation, c be a new constant and t be a ground term not containing c. Then*

$$E(c) \cup \{t \approx c\} \models e(c) \quad \Leftrightarrow \quad E(t) \models e(t).$$

Proof. The only non-obvious direction is '$\Rightarrow$'. Since t does not include c, $E(c) \cup \{t \approx c\} \models e(c)$ holds with c replaced by t, but then the equation $t \approx t$ is simply superfluous. □

Clearly, S is solvable if and only if the set of rigid equations in S that are not redundant, is solvable. We will use the following lemma.

Lemma 4. *Let $E(x) \vDash_\forall s_0(x) \approx t_0(x)$ be a non-redundant rigid equation of one variable x and let c be a new constant. There exists a finite set of ground terms T such that, for any ground term t not containing c the following holds:*

$$E(t) \models s_0(t) \approx t_0(t) \quad \Leftrightarrow \quad E(c) \models t \approx s \text{ for some } s \in T.$$

Furthermore, T can be obtained in polynomial time.

Proof. Let T' be the set $\mathit{Terms}(E(c) \cup \{s_0(c) \approx t_0(c)\})$. Let

$$T = \{\, s \in T' \mid E(c) \cup \{s \approx c\} \models s_0(c) \approx t_0(c)\,\}.$$

Note that T may be empty. Let t be any ground term that does not contain c. By using Lemma 3, it is enough to prove that the following statements are equivalent:

1. $E(c) \cup \{t \approx c\} \models s_0(c) \approx t_0(c)$,
2. $E(c) \models t \approx s$ for some $s \in T$.

(2 $\Rightarrow$ 1) Assume that statement 2 holds. Then there is a term s in T such that $[t]_{E(c)} = [s]_{E(c)}$. Since $s \in T$, we know that $E(c) \cup \{s \approx c\} \models s_0(c) \approx t_0(c)$. Hence $E(c) \cup \{t \approx c\} \models s_0(c) \approx t_0(c)$.
(1 $\Rightarrow$ 2) Assume that statement 1 holds. First we prove that $[t]_{E(c)} \in [T']_{E(c)}$. Suppose (by contradiction) that this is not so. But then it follows from Lemma 1 that $E(c) \models s_0(c) \approx t_0(c)$, contradicting that the rigid equation is not redundant. So there is a term s in T' such that $[t]_{E(c)} = [s]_{E(c)}$, and thus (by statement 1) $E(c) \cup \{s \approx c\} \models s_0(c) \approx t_0(c)$. Hence $s \in T$ and statement 2 follows.

Finally, to prove that T can be obtained in polynomial time, observe that the size of T' is proportional to the size of the rigid equation, and to decide if some term in T' belongs to T takes polynomial time by Theorem 2. □

Decidability of SREU with one variable can now be proved by combining Lemma 4 with a result by Brainerd [3] (that states that, given a set R of a ground rewrite rules and a set T of ground terms, then the set $\{\, t \mid (\exists s \in T)\; t \xrightarrow{*}_R s \,\}$ is recognizable) and by using elementary finite tree automata theory. However, this proof would not give us the computational complexity result that is established below.

4 Computational Complexity of SREU with One Variable

In this section we show formally that SREU with one variable is decidable, and in fact EXPTIME-complete. We first introduce the following definition.

► The *intersection nonemptiness problem of DTAs* or *DTAI* is the following decision problem. Given a collection $\{ A_i \mid 1 \leq i \leq n \}$ of DTAs, is $\bigcap_{i=1}^{n} T(A_i)$ nonempty?

The EXPTIME-completeness of the intersection nonemptiness problem of finite tree automata has been observed by other authors [22,27,44] and strictly proved for DTAs in Veanes [50].

Theorem 5 (Veanes). *DTAI is EXPTIME-complete.*

We will first show that SREU with one variable reduces to DTAI in polynomial time. This establishes the inclusion of SREU with one variable in EXPTIME. We then show that DTAI reduces to SREU with one variable, which shows the hardness part. The construction that we will use is in fact based on a construction in de Kogel [11, Theorems 4.1 and 4.2] that is based on Shostak's congruence closure algorithm [45].[1] A similar construction is used also in Gurevich and Voronkov [30].

4.1 SREU with one variable is in EXPTIME

In the following we will assume that none of the rigid equations are redundant. Lemma 4 tells us that the set of solutions of a rigid equation $E(x) \models_{\forall} e(x)$ with one variable is given by the union of a finite number of congruence classes

$$\bigcup_{s \in T} \{ t \mid E(c) \models s \approx t \},$$

where $T \subseteq \mathit{Terms}(E(c) \cup \{e(c)\})$ and c is a new constant. We will now give a polynomial time construction of a DTA that recognizes the above set of terms. Our considerations lead naturally to the following definition. Let E be a set of ground equations and T a subset of $\mathit{Terms}(E)$.

► A DTA $A = (Q, \Sigma, R, F)$ is *presented by* (E, T) if A has the following form (modulo renaming of states). First, let q_C be a new state for each $C \in [\mathit{Terms}(E)]_E$.

$$\begin{aligned}
Q &= \{ q_C \mid C \in [\mathit{Terms}(E)]_E \}, \\
\Sigma &= \Sigma(E), \\
F &= \{ q_C \mid C \in [T]_E \}, \\
R &= \{ f(q_{[t_1]_E}, \ldots, q_{[t_n]_E}) \to q_{[t]_E} \mid t = f(t_1, \ldots, t_n) \in \mathit{Terms}(E) \}.
\end{aligned}$$

[1] De Kogel does not use tree automata but the main idea is the same.

It is clear that the above automaton is well defined. It follows from elementary properties of congruence relations that A is deterministic and thus R is reduced. Note that for each constant c in $\Sigma(E)$, there is a rule $c \to q_{[c]_E}$ in R. Note also that for any equation $s \approx t$ in E, both s and t reduce to the same normal form $q_{[s]_E} = q_{[t]_E}$ with respect to R, since they belong to *Terms*(E). We will use the following lemma.

Lemma 6. *Let E be a set of ground equations and $T \subseteq$ Terms(E). Let A be a DTA presented by (E, T). Then*

1. $T(A) = \{\, t \in \mathcal{T}_{\Sigma(E)} \mid (\exists s \in T)\, E \models t \approx s \,\}$,
2. *A can be constructed in polynomial time from E and T.*

Proof. To prove the first statement, consider a Σ-structure $\mathfrak{A}$ with the universe $\{\, t{\downarrow_R} \mid t \in \mathcal{T}_{\Sigma \cup \Gamma} \,\}$ and the interpretation function such that $t^{\mathfrak{A}} = t{\downarrow_R}$ for all $t \in \mathcal{T}_\Sigma$. Clearly, it is enough to prove that, for all $t, s \in \mathcal{T}_\Sigma$,

$$E \models t \approx s \quad \Leftrightarrow \quad \mathfrak{A} \models t \approx s.$$

For a proof of this statement see de Kogel [11].

The second part is proved as follows. The number of terms in *Terms*(E) is proportional to the size of E. It follows by Theorem 2 that the time complexity of the construction of Q, i.e., the time complexity to partition *Terms*(E) into congruence classes, is polynomial. The rest is obvious. □

We prove now that SREU with one variable is in EXPTIME.

Lemma 7. *SREU with one variable is in EXPTIME.*

Proof. Let $S(x) = \{\, S_i(x) \mid 1 \le i \le n \,\}$ be a system of rigid equations. Assume, without loss of generality, that none of the rigid equations is redundant. Let $S_i(x) = E_i(x) \models_\forall e_i(x)$. Let Σ be the signature of S. Use Lemma 4 to obtain, for each i, $1 \le i \le n$, a set of ground terms T_i in polynomial time such that, for all t in $\mathcal{T}_\Sigma$,

$$E_i(t) \models e_i(t) \quad \Leftrightarrow \quad E_i(c) \models t \approx s \text{ for some } s \in T_i.$$

Use now Lemma 6 to obtain (in polynomial time) a DTA A_i that presents $(E_i(c), T_i)$, for $1 \le i \le n$. It follows by Lemma 4 and the first part of Lemma 6 that

$$T(A_i) = \{\, t \in \mathcal{T}_\Sigma \mid E_i(t) \models e_i(t) \,\} \quad (\text{for } 1 \le i \le n).$$

Thus, θ is a solution to $S(x)$ if and only if $x\theta$ is recognizable by all $T(A_i)$. Consequently, $S(x)$ is solvable if and only if $\bigcap_{i=1}^n T(A_i)$ is nonempty. The lemma follows, since DTAI is in EXPTIME. □

4.2 SREU with one variable is EXPTIME-complete

We will reduce DTAI to SREU with one variable to establish the hardness part. First, let us state some simple but useful facts.

Lemma 8. *Let $A = (Q, \Sigma, R, F)$ be a DTA, f be a unary function symbol not in Σ, and c be a constant not in Q or Σ. Let*

$$S(x) = (R \cup \{\, f(q) \to c \mid q \in F \,\} \models_{\forall} x \approx c).$$

Then, for all θ such that $x\theta \in \mathcal{T}_{\Sigma \cup \{f\}}$,

$$\theta \textit{ solves } S(x) \quad \Leftrightarrow \quad x\theta = f(t) \textit{ for some } t \in T(A).$$

Proof. Let $E = R \cup \{\, f(q) \to c \mid q \in F \,\}$. From the fact that R is reduced and that $f(q)$ is irreducible in R and c is irreducible in E, follows that E is reduced and thus canonical. So, for any $x\theta \in \mathcal{T}_{\Sigma \cup \{f\}}$, θ solves $S(x)$ if and only if (since E is ground) $E \models x\theta \approx c$ if and only if $x\theta \xrightarrow{*}_E c$. But

$$\begin{aligned} x\theta \xrightarrow{*}_E c &\Leftrightarrow x\theta \xrightarrow{*}_E f(q) \longrightarrow c \text{ for some } q \in F \\ &\Leftrightarrow x\theta = f(t) \text{ for some } t \in \mathcal{T}_\Sigma \text{ and } t \xrightarrow{*}_R q \\ &\Leftrightarrow x\theta = f(t) \text{ for some } t \in T(A). \end{aligned}$$

□

For a given signature Σ, and some constant c in it, let us denote by $S_\Sigma(x)$ the following rigid equation:

$$S_\Sigma(x) = (\{\, \sigma(c, \ldots, c) \approx c \mid \sigma \in \Sigma \,\} \models_{\forall} x \approx c).$$

The following lemma is elementary [18].

Lemma 9. *For all θ, θ solves $S_\Sigma(x)$ if and only if $x\theta \in \mathcal{T}_\Sigma$.*

We have now reached the point where we can state and easily prove the following result.

Theorem 10. *SREU with one variable is EXPTIME-complete.*

Proof. Inclusion in EXPTIME follows by Lemma 7. Let $\{\, A_i \mid 1 \leq i \leq n \,\}$ be a collection of DTAs with a signature Σ. Let f be a new unary function symbol and $\Sigma' = \Sigma \cup \{f\}$. For each A_i, let $S_i(x)$ be the rigid equation given by Lemma 8. So, for all θ such that $x\theta \in \mathcal{T}_{\Sigma'}$,

$$\theta \text{ solves } S_i(x) \quad \Leftrightarrow \quad x\theta = f(t) \text{ for some } t \in T(A_i).$$

Let

$$S(x) = \{\, S_i(x) \mid 1 \leq i \leq n \,\} \cup \{S_{\Sigma'}(x)\}.$$

It follows by Lemma 9 that for any θ that solves $S(x)$, $x\theta$ is in $\mathcal{T}_{\Sigma'}$. Hence, by Lemma 8, $S(x)$ is solvable if and only if $\bigcap_{i=1}^n T(A_i)$ is nonempty. Obviously, $S(x)$ has been constructed in polynomial time. The statement follows, since DTAI is EXPTIME-complete. □

So in the general case, SREU is already intractable with one variable. It should be noted however that the exponential behavior is strongly related to the unboundedness of the number of rigid equations. (See Section 4.3.)

4.3 Bounded SREU with One Variable

The exponential worst case behavior of SREU with one variable is strongly related to the unboundedness of the number of rigid equations, and not to the size or other parameters of the rigid equations. This behavior is explained by the fact that the intersection nonemptiness problem of a family of DTAs is in fact the nonemptiness problem of the corresponding direct product of the family. The size of a direct product of a family of DTAs is proportional to the product of the sizes of the members of the family, and the time complexity of the nonemptiness problem of a DTA is polynomial.

- ► *Bounded SREU* is SREU with a number of rigid equations that is bounded by some fixed positive integer.

We will use the following definition.

- ► The *nonemptiness* problem of TAs is the following decision problem. Given a TA A, is $T(A)$ nonempty?

The nonemptiness problem of DTAs is basically the problem of generability of finitely presented algebras. The latter problem is P-complete [32] and thus, by a very simple reduction, also the DTA nonemptiness problem is P-complete [50].[2] For bounded SREU with one variable we get the following result.

Theorem 11. *Bounded SREU with one variable is P-complete.*

Proof. Let the number of rigid equations be bounded by some fixed positive integer n. P-hardness follows from Theorem 2. Without loss of generality consider a system

$$S(x) = \{\, S_i(x) \mid 1 \leq i \leq n \,\}$$

of exactly n rigid equations. For each S_i construct a DTA A_i in polynomial time, like in Lemma 7. Let A be the DTA that recognizes $\bigcap_{i=1}^{n} T(A_i)$. For example, A can be the direct product of $\{\, A_i \mid 1 \leq i \leq n \,\}$ (Gécseg and Steinby [26]). It is straightforward to construct A in time that is proportional to the product of the sizes of the A_i's. Hence A is obtained in polynomial time (because n is fixed) and $T(A)$ is nonempty if and only if $S(x)$ is solvable. □

[2] The book of Greenlaw, Hoover and Ruzzo [28] includes an excellent up-to-date survey of around 150 P-complete problems, including generability.

4.4 Monadic SREU with One Variable

When we restrict the signature to consist of function symbols of arity ≤ 1, i.e., when we consider the so-called *monadic* SREU then the complexity bounds are different. We can note that DTAs restricted to signatures with just unary function symbols correspond to classical deterministic finite automata or DFAs. It was proved by Kozen that the computational complexity of the intersection nonemptiness problem of DFAs is PSPACE-complete [33]. So, by using this fact we can see that Theorem 10 proves that monadic SREU with one variable is PSPACE-complete.

Monadic SREU is studied in detail elsewhere [30]. We can note that, in general, the decidability of monadic SREU is still an open problem. There is also a very close connection between monadic SREU and the prenex fragment of intuitionistic logic with equality restricted to function symbols of arity ≤ 1 [16].

5 United One Variable Case

In this section we extend the decidability result of SREU with one variable to SREU with multiple variables with the following syntactical restriction on the structure of each rigid equation. We say that a system of rigid equations has the *united one variable property* if each rigid equation $E \models_\forall e$ in it satisfies the following conditions:

1. Either $E \models_\forall e$ includes at most one variable, or
2. E is ground and e has the form $x \approx y$ for two variables x and y.

SREU restricted to systems with the united one variable property is called *united one variable SREU*. The main result of this section is that the united one variable SREU is decidable. The proof is by reduction to the decidable first-order theory of ground rewrite systems [10].

5.1 The Decidable Theory GRS

Now we formally define the *theory of ground rewrite systems* or *GRS*. Consider a signature Σ that contains all the function symbols and constants that we are going to need in the sequel. Let Γ be the following signature constructed from Σ.

- For each term t in $\mathcal{T}_\Sigma$, let $\bar{t}$ be a constant in Γ.
- For each ground rewrite system E over $\mathcal{T}_\Sigma$, let R_E be a new binary relation symbol in Γ.[3]

Now, let $\mathfrak{A}$ be the following Γ-structure. The universe of $\mathfrak{A}$ is $\mathcal{T}_\Sigma$ and the interpretation function of $\mathfrak{A}$ is defined as follows. Note that the only ground terms in the signature of $\mathfrak{A}$ are the constants $\bar{t}$ for $t \in \mathcal{T}_\Sigma$, since there are no function symbols in Γ of positive arity.

[3] In the original definition of GRS [10] there are two more relation symbols for each E, but we do not use them here.

1. For each constant $\bar{t} \in \Gamma$, $\bar{t}^{\mathfrak{A}} = t$.
2. For each relation symbol $R_E \in \Gamma$, $R_E^{\mathfrak{A}}$ is the rewrite relation $\xrightarrow{*}_E$.

We can now define GRS as the first-order theory of $\mathfrak{A}$, i.e.,

$$\mathrm{GRS} = \{\, \varphi \text{ a sentence in } \Gamma \mid \mathfrak{A} \models \varphi \,\}.$$

We use the following result [10].

Theorem 12 (Dauchet–Tison). *GRS is decidable.*

The proof of Theorem 12 is by reduction to finite tree automata. In particular, it involves, for each ground rewrite system, a construction of a "ground tree transducer" that is a pair of a bottom-up and a top-down finite tree automaton, and defines the rewrite relation that is related with that rewrite system [8,9]. When GRS is restricted to *reduced* ground rewrite systems (which is enough in our case) one can give an easier proof of Theorem 12 by reduction to the decidable weak monadic second-order theory of the binary tree or WS2S.[4] See Thomas [49] for a survey of related topics.

5.2 Reduction to GRS

We use the following lemma. In the following we consider rigid equations in a fixed signature Σ that contains at least one constant. We also assume that we have a sufficiently large supply of new constants.

Lemma 13. *Let $E(x) \models_{\forall} e(x)$ be a non-redundant rigid equation with one variable x. There is a formula $\varphi(x)$ in the language of GRS such that, for all ground terms t,*

$$\mathfrak{A} \models \varphi(\bar{t}) \quad \Leftrightarrow \quad E(t) \models e(t) \text{ and } t \in \mathcal{T}_\Sigma.$$

Proof. Let c be a new constant and use Lemma 4 to obtain a finite set T ($\subseteq \mathcal{T}_{\Sigma \cup \{c\}}$) of ground terms such that, for all ground terms t not containing c,

$$E(t) \models e(t) \quad \Leftrightarrow \quad E(c) \models t \approx s \text{ for some } s \in T.$$

Let $E_\Sigma = \{\, f(c_1, \ldots, c_1) \approx c_1 \mid f \in \Sigma \,\}$[5] where c_1 is some constant in Σ. Consider both $E(c)$ and E_Σ as rewrite systems, with equations as rules in both directions. Let $\varphi(x)$ be the following formula:

$$\varphi(x) = (\bigvee_{s \in T} R_{E(c)}(x, \bar{s})) \wedge R_{E_\Sigma}(x, \bar{c}_1).$$

It follows by definition of $\mathfrak{A}$ that, for all ground terms t,

$$\begin{aligned}
\mathfrak{A} \models \varphi(\bar{t}) &\Leftrightarrow \mathfrak{A} \models \bigvee_{s \in T} R_{E(c)}(\bar{t}, \bar{s}) \text{ and } \mathfrak{A} \models R_{E_\Sigma}(\bar{t}, \bar{c}_1) \\
&\Leftrightarrow t \xrightarrow{*}_{E(c)} s \text{ for some } s \in T, \text{ and } t \xrightarrow{*}_{E_\Sigma} c_1 \\
&\Leftrightarrow E(c) \models t \approx s \text{ for some } s \in T, \text{ and } t \in \mathcal{T}_\Sigma \\
&\Leftrightarrow E(t) \models e(t) \text{ and } t \in \mathcal{T}_\Sigma,
\end{aligned}$$

[4] Such a proof has been given by Gurevich and Veanes.

[5] Note that $f(c_1, \ldots, c_1)$ stands for f whenever f is a constant.

where the last equivalence holds by the above, because c is not in Σ. □

We can now prove the following.

Theorem 14. *United one variable SREU is decidable.*

Proof. Let $S = \{ S_i \mid 1 \leq i \leq n \}$ be a system of rigid equations with the united one variable property. Assume, without loss of generality, that none of the rigid equations in S is redundant. For each rigid equation $S_i(x)$ in S with one variable x let $\varphi_i(x)$ be the formula given by Lemma 13. For each rigid equation $S_i(x,y) = E_i \models_\forall x \approx y$ in S, where E_i is ground, and x and y are variables, consider E_i as a ground rewrite system with equations as rules in both directions and let $\varphi_i(x,y) = R_{E_j}(x,y)$. So, for all ground terms t and s,

$$E_i \models t \approx s \quad \Leftrightarrow \quad t \xrightarrow{*}_{E_i} s \quad \Leftrightarrow \quad \mathfrak{A} \models R_{E_i}(\bar{t}, \bar{s}).$$

Finally, let φ be the existential closure of the conjunction of all the φ_i's. It is straightforward to verify that φ is a theorem in GRS if and only if S is solvable. The statement follows by Theorem 12. □

The computational complexity of the united one variable SREU is not known, we know only that it is at least EXPTIME-hard. It also remains to be investigated if there are other decidable extensions of the one variable case. We can also note the following result. The $\exists$-*fragment* of GRS is the set of prenex formulas in GRS with one existential quantifier.

Corollary 15. *The $\exists$-fragment of GRS is EXPTIME-hard.*

Proof. From the proof of Theorem 14 it is clear that the reduction from SREU with one variable to GRS can be performed in polynomial time and that the resulting formula is a prenex formula with one existential quantifier. The statement follows now from Theorem 10. □

6 Implications to the Prenex Fragment of Intuitionistic Logic

The *prenex fragment* of intuitionistic logic is the collection of all intuitionistically provable prenex formulas. Many new decidability results about the prenex fragment have been obtained quite recently by Degtyarev and Voronkov [16–18] and Voronkov [53]. Some of these results are:

1. Decidability, and in particular PSPACE-completeness, of the prenex fragment of intuitionistic logic *without* equality [53].
2. Prenex fragment of intuitionistic logic *with* equality but *without* function symbols is PSPACE-complete [16]. Decidability of this fragment was proved in Orevkov [42].

3. Prenex fragment of intuitionistic logic with equality in the language with one unary function symbol is decidable [16].
4. $\exists^*$-fragment of intuitionistic logic with equality is undecidable [17,18].

In some of the above results, the corresponding result has first been obtained for a fragment of SREU with similar restrictions. For example, the proof of the last statement is based on the undecidability of SREU. The undecidability of the $\exists^*$-fragment is improved in Veanes [51] where it is proved that, already the

5. $\exists\exists$-fragment of intuitionistic logic with equality is undecidable.

With the following result we obtain a complete characterization of decidability of the prenex fragment of intuitionistic logic with equality with respect to quantifier prefix.

Theorem 16. *The $\forall^*\exists\forall^*$-fragment of intuitionistic logic with equality is decidable and EXPTIME-hard.*

Proof. Intuitionistic provability of any formula in the $\forall^*\exists\forall^*$-fragment can be reduced to solvability of SREU with one variable [16]. Conversely, solvability of a system of rigid equations with one variable reduces trivially to provability of a corresponding formula in the $\exists$-fragment [16]. The statement follows by Theorem 10. $\square$

Remark The undecidability of the $\exists\exists$-fragment holds if there is one binary function symbol in the signature. The reduction in Theorem 16 from a $\forall^*\exists\forall^*$-formula to SREU with one variable may take exponential time, so the precise computational complexity for this fragment is unknown at this moment.

Other fragments Decidability problems for other fragments of intuitionistic logic have been studied by Orevkov [41,42], Mints [40], Statman [47] and Lifschitz [36]. Orevkov proves that the $\neg\neg\forall\exists$-fragment of intuitionistic logic with function symbols is undecidable [41]. Lifschitz proves that intuitionistic logic with equality and without function symbols is undecidable, i.e., that the pure constructive theory of equality is undecidable [36]. Orevkov shows decidability of some fragments (that are close to the prenex fragment) of intuitionistic logic with equality [42]. Statman proves that the intuitionistic propositional logic is PSPACE-complete [47].

7 Current Status of SREU and Open Problems

Here we briefly summarize the current status of SREU. The first decidability proof of rigid E-unification is given in Gallier, Narendran, Plaisted and Snyder [24]. Recently a simpler proof, without computational complexity considerations, has been given by de Kogel [11]. We start with the **solved cases**:

– Rigid E-unification with ground left-hand side is NP-complete [34]. Rigid E-unification in general is NP-complete and there exist finite complete sets of unifiers [24,23].

- Rigid E-unification with one variable is P-complete. Or, more generally, SREU with one variable and a bounded number of rigid equations is P-complete (Theorem 11).
- If all function symbols have arity ≤ 1 (the *monadic* case) then it follows that SREU is PSPACE-hard [27]. If only one unary function symbol is allowed then the problem is decidable [14,13]. If only constants are allowed then the problem is NP-complete [14] if there are at least two constants.
- About the monadic case it is known that SREU with more than two unary function symbols is decidable if and only if it is decidable with just two unary function symbols [14].
- If the left-hand sides are ground then the monadic case is decidable [30]. Monadic SREU with one variable is PSPACE-complete [30].
- The word equation solving [38] (unification under associativity), which is an extremely hard problem with no interesting known computational complexity bounds, can be reduced to monadic SREU [13].
- Monadic SREU is equivalent to a non-trivial extension of word equations [30].
- Monadic SREU is equivalent to the provability problem of the prenex fragment of intuitionistic logic with equality with function symbols of arity ≤ 1 [16].
- In general SREU is undecidable [15]. Moreover, it is undecidable with ground left-hand sides [43]. Furthermore, SREU is undecidable with three rigid equations with ground left-hand sides and two variables [51,29].
- SREU with one variable is decidable, in fact EXPTIME-complete (Theorem 10).
- There is a logspace reduction from second-order unification to SREU [18]. In fact, SREU is logspace equivalent to second-order unification [52].

Note also that SREU is decidable when there are no variables, since each rigid equation can be decided for example by using any congruence closure algorithm or ground term rewriting technique. Actually, the problem is then P-complete because the uniform word problem for ground equations is P-complete [32]. Further problems that are related to SREU are discussed in Voronkov [56,55]. The main **unsolved cases** are:

? Decidability of monadic SREU [30].
? Decidability of SREU with *two* rigid equations.

Both problems are highly non-trivial.

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