Goal-Directed E-Unification

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Abstract. We give a general goal directed method for solving the E-unification problem. Our inference system is a generalization of the inference rules for Syntactic Theories, except that our inference system is proved complete for any equational theory. We also show how to easily modify our inference system into a more restricted inference system for Syntactic Theories, and show that our completeness techniques prove completeness there also.

1 Introduction

E-unification [1] is a problem that arises in several areas of computer science, including automated deduction, formal verification and type inference. The problem is, given an equational theory E and a goal equation $u \approx v$, to find the set of all substitutions θ such that $u\theta$ and $v\theta$ are identical modulo E. In practice, it is not necessary to find all such substitution. We only need to find a set from which all such substitutions can be generated, called a *complete set of E-unifiers.*

The decision version of E-unification (Does an E-unifier exist?) is an undecidable problem, even for the simpler *word problem* which asks if all substitutions θ will make $u\theta$ and $v\theta$ equivalent modulo E. However there are procedures which are *complete* for the problem. Complete, in this sense, means that each E-unifier in a complete set will be generated eventually. However, because of the undecidability, the procedure may continue to search for an E-unifier forever, when no E-unifier exists.

One of the most successful general methods for solving the E-unification problem has been Knuth-Bendix Completion[12] (in particular, Unfailing Completion[2]) plus Narrowing[7]. This procedure deduces new equalities from E. If the procedure ever halts, it solves the word problem. However, because of the undecidability, Knuth-Bendix Completion cannot always halt.

Our goal in this paper is to develop an alternative E-unification procedure. Why do we want an alternative to Knuth-Bendix Completion? There are several reasons. First, there are simple equational theories for which Completion does not halt. An example is the equational theory $E = \{f(g(f(x))) \approx g(f(x))\}$. So then it is impossible to decide any word problem in this theory, even a simple

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example like $a \approx b$, which is obviously not true. Using our method, examples like this will quickly halt and say there is no solution.

A related deficiency of Completion is that it is difficult to identify classes of equational theories where the procedure halts, and to analyze the complexity of solving those classes. That is our main motivation for this line of research. We do not pursue that subject in this paper, since we first need to develop a complete inference system. That subject is addressed in [14, 15], where we deal classes of equations where the E-unification is decidable in an inference system similar to the one given in this paper.

Another aspect of Completion is that it is insensitive to the goal. It is possible to develop heuristics based on the goal, but problems like the example above still exist, because of the insensitivity to the goal. The method we develop in this paper is goal directed, in the sense that every inference step is a step backwards from the goal, breaking the given goal into separate subgoals. Therefore we call our method a goal directed inference system for equational reasoning. This quality of goal-directedness is especially important when combining an equational inference system with another inference system. Most of the higher order inference systems used for formal verification have been goal directed inference systems. Even most inference systems for first order logic, like OTTER, are often run with a set of support strategy. For things like formal verification, we need equality inference systems that can be added as submodules of previously existing inference systems. We believe that the best method for achieving this is to have a goal directed equality inference system.

We do not claim that our procedure is the first goal directed equational inference system. Our inference system is similar to the inference system Syntactic Mutation first developed by Claude Kirchner [8, 10]. That inference system applies to a special class of equational theories called Syntactic Theories. In such theories, any true equation has an equational proof with at most one step at the root. The problem of determining if an equational theory is syntactic is undecidable[11]. In the Syntactic Mutation inference system, it is possible to determine which inference rule to apply next by looking at the root symbols on the two sides of a goal equation. This restricts which inference rules can be applied at each point, and makes the inference system more efficient than a blind search.

Our inference system applies to every equational theory, rather than just Syntactic Theories. Therefore, it would be incomplete for us to examine the root symbol at both sides of a goal equation. However, we do prove that we may examine the root symbol of one side of an equation to decide which inference rule to apply. Other than that, our inference system is similar to Syntactic Mutation. We prove that our inference system is complete. The Syntactic Mutation rules were never proved to be complete. In [9], it is stated that there is a problem proving completeness because the Variable Elimination rule (called "Replacement" there) does not preserve the form of the proof. We think we effectively deal with that problem.

There is still an open problem of whether the Variable Elimination rule can be applied eagerly.[1] We have not solved that problem. But we have avoided those problems as much as possible. The inefficiency of the procedure comes from cases where one side of a goal equation is a variable. We prove that any equation where both sides are variables may be ignored without losing completeness. We also orient equations so that inference rules are applied to the nonvariable side of an equation. This gives some of the advantages of Eager Variable Elimination.

Other similar goal-directed inference procedures are given in [4, 5]. The inference system from [4] is called BT. The one in [5] is called **Trans**. The main difference between our results and the results in those papers all of our inference rules involve a root symbol of a term in the goal. This limits the number of inference rules that can be applied at any point. For BT and **Trans** there are inference rules that only involve variables in the goal. These rules allow an explosion of inferences at each step, which expands the search space. This is similar to the situation in Paramodulation completeness proofs required paramodulation into variables until Brand[3] proved that this was not necessary for completeness. We believe that the completeness results in this paper are analogous to the results of Brand, but for goal-directed E-unification. In the case of Paramodulation, the results of Brand prove essential in practice. Another difference between our results and BT and **Trans** is that those papers require Variable Elimination, while ours do not. Gallier and Snyder[4] pointed out the problem of inference rules involving variables. However, their solution was to design a different inference system, called T, that allows inferences below the root. Our results solve this problem without requiring inferences below the root. The problem of Eager Variable Elimination was first presented in [4].

The format of the paper is to first give some preliminary definitions. Then present our inference system. After a discussion of normal form, we present soundness results. In order to prove completeness, we first give a bottom-up method for deducing ground equations, then use that method to prove completeness of our goal-directed method. After that we show how our completeness technique can be applied to Syntactic Theories to show completeness of a procedure similar to Syntactic Mutation. Finally, we conclude the paper. All missing proofs are in [13].

2 Preliminaries

We assume we are given a set of variables and a set of uninterpreted function symbols of various arities. An arity is a non-negative integer. *Terms* are defined recursively in the following way: each variable is a term, and if $t_1, \cdots, t_n$ are terms, and f is of arity $n \geq 0$, then $f(t_1, \cdots, t_n)$ is a term, and f is the symbol at the *root* of $f(t_1, \cdots, t_n)$. A term (or any object) without variables is called *ground*. We consider equations of the form $s \approx t$, where s and t are terms. Please note that throughout this paper these equations are considered to be oriented,

[1] See [16] for a discussion of the problem and a solution for a very specific case.

so that $s \approx t$ is a different equation that $t \approx s$. Let E be a set of equations, and $u \approx v$ be an equation, then we write $E \models u \approx v$ (or $u =_E v$) if $u \approx v$ is true in any model containing E. If G is a set of equations, then $E \models G$ means that $E \models e$ for all e in G.

A *substitution* is a mapping from the set of variables to the set of terms, such that it is almost everywhere the identity. We identify a substitution with its homomorphic extension. If θ is a substitution then $Dom(\theta) = \{x \mid x\theta \neq x\}$. A substitution θ is an *E-unifier* of an equation $u \approx v$ if $E \models u\theta \approx v\theta$. θ is an *E-unifier* of a set of equations G if θ is an E-unifier of all equations in G.

If σ and θ are substitutions, then we write $\sigma \leq_E \theta[Var(G)]$ if there is a substitution ρ such that $E \models x\sigma\rho \approx x\theta$ for all x appearing in G. If G is a set of equations, then a substitution θ is a *most general unifier of* G, written $\theta = mgu(G)$ if θ is an E unifier of G, and for all E unifiers σ of G, $\theta \leq_E \sigma[Var(G)]$. A complete set of E-unifiers of G, is a set of E-unifiers Θ of G such that for all E-unifiers σ of G, there is a θ in Θ such that $\theta \leq_E \sigma[Var(G)]$.

3 The Goal Directed Inference Rules

In this section, we will give a set of inference rules for finding a complete set of E-unifiers of a goal G, and in the following sections we prove that, for every goal G and substitution θ such that $E \models G\theta$, G can be converted into a *normal form* (see Section 4), which determines a substitution which is more general than θ. The inference rules decompose an equational proof by choosing a potential step in the proof and leaving what is remaining when that step is removed.

We define two special kinds of equations appearing in the goal G. An equation of the form $x \approx y$ where x and y are both variables is called a *variable-variable* equation. An equation $x \approx t$ appearing in G where x only appears once in G is called *solved*.

As in Logic Programming, we can have a selection rule for goals. For each goal G, we don't-care nondeterministically select an equation $u \approx v$ from G, such that $u \approx v$ is not a variable-variable equation and $u \approx v$ is not solved. We say that $u \approx v$ is *selected in* G. If there is no such equation $u \approx v$ in the goal, then nothing is selected. We will prove that if nothing is selected, then the goal is in normal form and a most general-E unifier can be easily determined.

There is a Decomposition rule.

Decomposition

$$\frac{\{f(s_1, \cdots, s_n) \approx f(t_1, \cdots, t_n)\} \cup G}{\{s_1 \approx t_1, \cdots, s_n \approx t_n\} \cup G}$$

where $f(s_1, \cdots, s_n) \approx f(t_1, \cdots, t_n)$ is selected in the goal.

This is just an application of the Congruence Axiom, in a goal-directed way. If f is of arity 0 (a constant) then this is a goal-directed application of Reflexivity.

We additionally add a second inference rule that is applied when one side of an equation is a variable.

Variable Decomposition

$$\frac{\{x \approx f(t_1, \cdots, t_n)\} \cup G}{\{x \approx f(x_1, \cdots, x_n)\} \cup (\{x_1 \approx t_1, \cdots, x_n \approx t_n\} \cup G)[x \mapsto f(x_1, \cdots, x_n)]}$$

where x is a variable, and $x \approx f(t_1, \cdots, t_n)$ is selected in the goal.

This is similar to the Variable Elimination rule for syntactic equalities. It can be considered a gradual form of Variable Elimination, since it is done one step at a time. This rule is the same as the rule that is called Imitation in **Trans** and Root Imitation in BT. We have chosen our name to emphasize its relationship with the Decomposition rule.

Now we add a rule called Mutate. We call it Mutate, because it is very similar to the inference rule Mutate that is used in the inference procedure for syntactic theories. Mutate is a kind of goal-directed application of Transitivity, but only transitivity steps involving equations from the theory.

Mutate

$$\frac{\{u \approx f(v_1, \cdots, v_n)\} \cup G}{\{u \approx s, t_1 \approx v_1, \cdots, t_n \approx v_n\} \cup G}$$

where $u \approx f(v_1, \cdots, v_n)$ is selected in the goal, and $s \approx f(t_1, \cdots, t_n) \in E$. [2] [3]

This rule assumes that there is an equational proof of the goal equation at the root of the equation (see Section 7). If one of the equations in this proof is $s \approx t$ then that breaks up the proof at the root into two separate parts. We have performed a Decomposition on one of the two equations that is created. Contrast this with the procedure for Syntactic Theories[8] which allows a Decomposition on both of the newly created equations. However, that procedure only works for Syntactic Theories, whereas our procedure is complete for any equational theory. The names of our inference rules are chosen to coincide with the names from [8]. In **Trans** the Mutate rule is called Lazy Narrowing, and in BT it is called Root Rewriting.

Next we give a Mutate rule for the case when one side of the equation from E is a variable.

Variable Mutate

$$\frac{\{u \approx f(v_1, \cdots, v_n)\} \cup G}{\{u \approx s\}[x \mapsto f(x_1, \cdots, x_n)] \cup \{x_1 \approx v_1, \cdots, x_n \approx v_n\} \cup G}$$

where $s \approx x \in E$, x is a variable, and $u \approx f(v_1, \cdots, v_n)$ is selected in the goal. This is called Application of a Trivial Clause in **Trans**, and it is a special case of Root Rewriting in BT.

We will write $G \longrightarrow G'$ to indicate that G goes to G' by one application of an inference rule. Then $\stackrel{*}{\longrightarrow}$ is the reflexive, transitive closure of $\longrightarrow$.

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[2] For simplicity, we assume that E is closed under symmetry.

[3] $s \approx f(t_1, \cdots, t_n)$ is actually a variant of an equation in E such that it has no variables in common with the goal. We assume this throughout the paper.

When an inference is performed, we may eagerly reorient any new equations in the goal. The way they are reoriented is don't-care nondeterministic, except that any equation of the form $t \approx x$, where t is not a variable and x is a variable, must be reoriented to $x \approx t$. This way there is never an equation with a nonvariable on the left hand side and a variable on the right hand side.

We will prove that the above inference rules solve a goal G by transforming it into normal forms representing a complete set of E-unifiers of G. There are two sources of non-determinism involved in the procedure defined by the inference rules. The first is "don't-care" non-determinism in deciding which equation to select in the goal, and in deciding which way to orient equations with non-variable terms on both sides. The second is "don't-know" non-determinism in deciding which rule to apply. Not all paths of inference steps will lead us to the normal form, and we do not know beforehand which ones do.

4 Normal Form

Notice that there are no inference rules that apply to an equation $x \approx y$, where x and y are both variables.[4] In fact, such an equation can never be selected. The reason is that so many Mutate and Variable Decomposition inferences could possibly apply to variable-variable pairs (as in BT) that we have designed the system to avoid them. That changes the usual definition of normal form, as in Standard Unification, and shows that inferences with variable-variable pairs are unnecessary.

Let G be a goal of the form $\{x_1 \approx t_1, \cdots, x_n \approx t_n, y_1 \approx z_1, \cdots, y_m \approx z_m\}$, where all x_i, y_i and z_i are variables, the t_i are not variables, and for all i and j,

1. $x_i \notin Var(t_j)$,
2. $x_i \neq y_j$ and
3. $x_i \neq z_j$.

Then G is said to be in *normal form*. Let σ_G be the substitution $[x_1 \mapsto t_1, \cdots x_n \mapsto t_n]$. Let τ_G be a most general (syntactic) unifier of $y_1 = z_1, \cdots, y_m = z_m$, with no new variables, such as what is calculated by a syntactic unification procedure. We know an mgu of only variable-variable equations must exist. Any such unifier effectively divides the variables into equivalence classes such that for each class E, there is some variable z in E such that $y\tau_G = z$ for all $y \in E$. Then we write $\hat{y} = z$. Note that for any E-unifier θ of G, $y\theta =_E \hat{y}\theta$. Finally, define θ_G to be the substitution $\sigma_G\tau_G$.

Proposition 1. *A goal with nothing selected is in normal form.*

Proof. Let G be a goal with nothing selected. Then all equations in G have a variable on the left hand side. So G is of the form $x_1 \approx t_1, \cdots, x_n \approx t_n, y_1 \approx z_1, \cdots, y_m \approx z_m$. Since nothing is selected, each equation $x_1 \approx t_1$ must be solved. So each x_i appears only once in G. Therefore the three conditions of normal form are satisfied. □

[4] This is similar to the flex-flex pairs for higher order unification in [6].

Now we will prove that the substitution represented by a goal in normal form is a most general E-unifier of that goal.

Lemma 1. *Let G be a set of equations in normal form. Then θ_G is a most general E-unifier of G.*

Proof. Let G be the goal $\{x_1 \approx t_1, \cdots, x_n \approx t_n, y_1 \approx z_1, \cdots, y_m \approx z_m\}$, such that for all i and j, $x_i \notin t_j$, $x_i \neq y_j$ and $x_i \neq z_j$. Let $\sigma_G = [x_1 \mapsto t_1, \cdots, x_n \mapsto t_n]$. Let $\tau_G = mgu(y_1 = z_1, \cdots, y_m = z_m)$. Let $\theta_G = \sigma_G \tau_G$. We will prove that θ_G is a most general E unifier of G.

Let i and j be integers such that $1 \leq i \leq n$ and $1 \leq j \leq n$. First we need to show that θ_G is a unifier of G, i.e. that $x_i\theta_G = t_i\theta_G$ and $y_j\theta_G = z_j\theta_G$. In other words, prove that $x_i\sigma_G\tau_G = t_i\sigma_G\tau_G$ and $y_j\sigma_G\tau_G = z_j\sigma_G\tau_G$. Since t_i, y_j and z_j are not in the domain of σ, this is equivalent to $t_i\tau_G = t_i\tau_G$ and $y_j\tau_G = z_j\tau_G$, which is trivially true, since τ_G is mgu of $\{y_1 \approx z_1, \cdots, y_m \approx z_m\}$.

Next we need to show that θ_G is more general than all other unifiers of G. So let θ be an E-unifier of G. In other words, $x_i\theta =_E t_i\theta$ and $y_j\theta =_E z_j\theta$. We need to show that $\theta_G \leq_E \theta[Var(G)]$. In particular, we will show that $G\theta_G\theta =_E G\theta$.

Then $x_i\theta_G\theta = x_i\sigma_G\tau_G\theta = t_i\tau_G\theta =_E t_i\theta =_E x_i\theta$. The only step that needs justification is the fact that $t_i\tau_G\theta =_E t_i\theta$. This can be verified by examining the variables of t_i. So let w be a variable in t_i. If $w \notin Dom(\tau_G)$ then obviously $w\tau_G\theta = w\theta$. If $w \in Dom(\tau_G)$ then w is some y_k. Note that $y_k\tau_G\theta = \hat{y_k}\theta =_E y_k\theta$. So $t_i\tau_G\theta =_E t_i\theta$.

Also, $y_j\theta_G\theta = y_j\sigma_G\tau_G\theta = y_j\tau_G\theta = \hat{y_j}\theta =_E y_j\theta$. Similarly for z_j. □

5 An Example

Here is an example of the procedure. (The selected equations are underlined.)

Example 1. Let $E = E_0 = \{ffx \approx gfx\}$, $G = G_0 = \{\underline{fgfy \approx ggfz}\}$.
By rule Mutate applied to G_0 we have
$G_1 = \{\underline{fgfy \approx ffx_1}, fx_1 \approx gfz\}$.
After Decomposition,
$G_2 = \{\underline{gfy \approx fx_1}, fx_1 \approx gfz\}$.
After Mutate,
$G_3 = \{\underline{gfy \approx gfx_2}, x_1 \approx fx_2, fx_1 \approx gfz\}$
After Decomposition is used 2 times on G_3,
$G_4 = \{y \approx x_2, \underline{x_1 \approx fx_2}, fx_1 \approx gfz\}$.
Variable Decomposition:
$G_5 = \{y \approx x_2, x_1 \approx fx_3, x_3 \approx x_2, \underline{ffx_3 \approx gfz}\}$.
Mutate:
$G_6 = \{y \approx x_2, x_1 \approx fx_3, x_3 \approx x_2, \underline{ffx_3 \approx ffx_4}, fx_4 \approx fz\}$.
$2\times$ Decomposition:
$G_7 = \{y \approx x_2, x_1 \approx fx_3, x_3 \approx x_2, x_3 \approx x_4, \underline{fx_4 \approx fz}\}$.
Decomposition:

$G_8 = \{y \approx x_2, x_1 \approx fx_3, x_3 \approx x_2, x_3 \approx x_4, x_4 \approx z\}$.

The extended θ' that unifies the goal G_0 is equal to: $[x_1 \mapsto fx_3][y \mapsto z, x_3 \mapsto z, x_2 \mapsto z, x_4 \mapsto z]$. θ' is equivalent on the variables of G to θ equal to: $[y \mapsto z]$.

6 Soundness

Theorem 1. *The above procedure is sound, i.e. if $G' \xrightarrow{*} G$ and G is in normal form, then $E \models G'\theta_G$.*

7 A Bottom Up Inference System

In order to prove the completeness of this procedure, we first define a bottom-up equational proof using Congruence and Equation Application rules. We prove that this equational proof is equivalent to the usual definition of equational proof for ground terms, which involves Reflexivity, Symmetry, Transitivity and Congruence.

$$\text{Congruence:} \quad \frac{s_1 \approx t_1 \cdots s_n \approx t_n}{f(s_1, \cdots, s_n) \approx f(t_1, \cdots, t_n)}$$

$$\text{Equation Application:} \quad \frac{u \approx s \quad t \approx v}{u \approx v},$$

if $s \approx t$ is a ground instance of an equation in E.

We define $E \vdash u \approx v$ if there is a proof of $u \approx v$ using the Congruence and Equation Application rules. If π is a proof, then $|\pi|$ is the number of steps in the proof. $|u \approx v|_E$ is the number of steps in the shortest proof of $u \approx v$.

We need to prove that $\{u \approx v \mid E \vdash u \approx v\}$ is closed under Reflexivity, Symmetry and Transitivity. First we prove Reflexivity.

Lemma 2. *Let E be an equational theory. Then $E \vdash u \approx u$ for all ground u.*

Next we prove closure under symmetry.

Lemma 3. *Let E be an equational theory such that $E \vdash u \approx v$ and $|u \approx v|_E = n$. Then $E \vdash v \approx u$, and $|v \approx u|_E = n$.*

Next we show closure under Transitivity.

Lemma 4. *Let E be an equational theory such that $E \vdash s \approx t$ and $E \vdash t \approx u$. Suppose that $|s \approx t|_E = m$ and $|t \approx u|_E = n$. Then $E \vdash s \approx u$, and $|s \approx u|_E \leq m + n$.*

Closure under Congruence is trivial. Now we put these lemmas together to show that anything true under the semantic definition of Equality is also true under the syntactic definition given here.

Theorem 2. *If $E \models u \approx v$, then $E \vdash u \approx v$, for all ground u and v.*

We can restrict our proofs to only certain kinds of proofs. In particular, if the root step of a proof tree is an Equation Application, then we can show there is a proof such that the proof step of the right child is not an Equation Application.

Lemma 5. *Let π be a proof of $u \approx v$ in E, which is derived by Equation Application, and whose right child is also derived by Equation Application. Then there is a proof π' of $u \approx v$ in E such that the root of π' is Equation Application but the right child is derived by Congruence, and $|\pi'| = |\pi|$.*

Proof. Let π be a proof of $u \approx v$ in E such that the step at the top is Equation Application, and the step at the right child is also Equation Application. We will show that there is another proof π' of $u \approx v$ in E such that $|\pi'| = |\pi|$, and the size of the right subtree of π' is smaller than the size of the right subtree of π. So this proof is an induction on the size of the right subtree of the proof.

Suppose $u \approx v$ is at the root of π and $u \approx s$ labels the left child n_1. Suppose the right child n_2 is labeled with $t \approx v$. Further suppose that the left child of n_2 is labeled with $t \approx w_1$ and the right child of n_2 is labeled with $w_2 \approx v$. Then $s \approx t$ and $w_1 \approx w_2$ must be ground instances of members of E.

$$\dfrac{\begin{array}{c}\pi_1\\ \vdots\\ n_1\colon u \approx s\end{array} \qquad \dfrac{\begin{array}{c}\pi_2\\ \vdots\\ t \approx w_1\end{array} \qquad \begin{array}{c}\pi_3\\ \vdots\\ w_2 \approx v\end{array}}{n_2\colon t \approx v}\ \text{Eq. App.}}{u \approx v}\ \text{Eq. App.}$$

Then we can let π' be the proof whose root is labeled with $u \approx v$, whose left child n_3 is labeled with $u \approx w_1$. Let the left child of n_3 be labeled with $u \approx s$ and the right child of n_3 be labeled with $t \approx w_1$. Also let the right child of the root n_4 be labeled with $w_2 \approx v$.

$$\text{Eq. App.}\ \dfrac{\text{Eq. App.}\ \dfrac{\begin{array}{c}\pi_1\\ \vdots\\ u \approx s\end{array} \qquad \begin{array}{c}\pi_2\\ \vdots\\ t \approx w_1\end{array}}{n_3\colon u \approx w_1} \qquad \begin{array}{c}\pi_3\\ \vdots\\ n_4\colon w_2 \approx v\end{array}}{u \approx v}$$

By induction, π' is a proof of $u \approx v$ of the same size as π. $\square$

8 Completeness of the Goal-Directed Inference System

Now we finally get to the main theorem of this paper, which is the completeness of the inference rules given in section 3. But first we need to define a measure on the equations in the goal.

Definition 1. *Let E be an equational theory and G be a goal. Let θ be a substitution such that $E \models G\theta$. We will define a measure μ, parameterized by θ and G. Define $\mu(G,\theta)$ as the multiset $\{|u\theta \approx v\theta|_E \mid u \approx v$ is an unsolved equation in $G\}$.*

The intension of the definition is that the measure of an equation in a goal is the number of steps it takes to prove that equation. However, solved equations are ignored.

Now, finally, the completeness theorem:

Theorem 3. *Suppose that E is an equational theory, G is a set of goal equations, and θ is a ground substitution. If $E \models G\theta$ then there exists a goal H in normal form such that $G \xrightarrow{*} H$ and $\theta_H \leq_E \theta[Var(G)]$.*

Proof. Let G be a set of goal equations, and θ a ground substitution such that $E \models G\theta$. Let $\mu(G,\theta) = M$. We will prove by induction on M that there exists a goal H such that $G \xrightarrow{*} H$ and $\theta_H \leq_E \theta[Var(G)]$.

If nothing is selected in G, then G must be in normal form, by Proposition 1. By Lemma 1, θ_G is the most general E-unifier of G, so $\theta_G \leq_E \theta[Var(G)]$.

If some equation is selected in G, we will prove that there is a goal G' and a substitution θ' such that $G \longrightarrow G'$, $\theta' \leq_E \theta[Var(G)]$, and $\mu(G',\theta') \leq \mu(G,\theta)$.

So assume that some equation $u \approx v$ is selected in G. Then G is of the form $\{u \approx v\} \cup G_1$. We assume that v is not a variable, because any term-variable equation $t \approx x$ is immediately reoriented to $x \approx t$. By Lemma 3, $|v\theta \approx u\theta|_E = |u\theta \approx v\theta|_E$. Also, according to our selection rule, a variable-variable equation is never selected. Since v is not a variable, it is in the form $f(v_1, \cdots, v_n)$. Let $|u\theta \approx v\theta|_E = m$.

Consider the rule used at the root of the smallest proof tree that $E \vdash u\theta \approx v\theta$. This was either an application of Congruence or Equation Application.

Case 1: Suppose the rule at the root of the proof tree of $E \vdash u\theta \approx v\theta$ is an Equation Application. Then there exists an extension θ' of θ and a ground instance $s\theta' \approx t\theta'$ of an equation $s \approx t$ in E, such that $E \vdash u\theta' \approx s\theta'$ and $E \vdash t\theta' \approx v\theta'$. Let $|u\theta' \approx s\theta'|_E = p$. Let $|t\theta' \approx v\theta'|_E = q$. Then $m = p+q+1$. We now consider two subcases, depending on whether or not t is a variable.

Case 1A: Suppose that t is not a variable. Then, we can assume that the rule at the root of the proof tree of $E \vdash t\theta' \approx v\theta'$, is Congruence. Otherwise, by Lemma 5, it could be converted into one, without making the proof any longer. So then t is of the form $f(t_1, \cdots, t_n)$, and the previous nodes of the proof tree are labeled with $t_1\theta' \approx v_1\theta', \cdots, t_n\theta' \approx v_n\theta'$. And, for each i, $|t_i\theta' \approx v_i\theta'|_E = q_i$ such that $1 + \Sigma_{1 \leq i \leq n} q_i = q$.
Therefore, there is an application of Mutate that can be applied to $u \approx v$, resulting in the new goal $G' = \{u \approx s, t_1 \approx v_1, \cdots, t_n \approx v_n\} \cup G_1$. Then $|u\theta' \approx s\theta'|_E = p$, and $|t_i\theta' \approx v_i\theta'|_E = q_i$ for all i, so $\mu(G'\theta') < \mu(G,\theta)$. By the induction assumption there is an H such that $G' \xrightarrow{*} H$ with $\theta_H \leq_E \theta'[Var(G')]$. This implies that $G \xrightarrow{*} H$. Also, $\theta_H \leq_E \theta'[Var(G)]$, since the variables of G are a subset of the variables of G'. Since $G\theta' = G\theta$, we know that $\theta_H \leq_E \theta[Var(G)]$.

Case 1B: Suppose that t is a variable. Then, by Lemma 5, we can assume that the rule at the root of the proof tree of $E \vdash t\theta' \approx v\theta'$ is Congruence. So then $t\theta'$ is of the form $f(t_1, \cdots, t_n)$, and the previous nodes of the proof tree are labeled with $t_1 \approx v_1\theta', \cdots, t_n \approx v_n\theta'$. And, for each i, $|t_i \approx v_i\theta'|_E = q_i$ such that $1 + \Sigma_{1 \leq i \leq n} q_i = q$.
Therefore, there is an application of Variable Mutate that can be applied to $u \approx v$, resulting in the new goal $G' = \{u \approx s[t \mapsto f(x_1, \cdots, x_n)], x_1 \approx v_1, \cdots, x_n \approx v_n\} \cup G_1\}$. We will extend θ' so that $x_i\theta' = t_i$ for all i. Then $|u\theta' \approx s\theta'|_E = p$, and $|x_i\theta' \approx v_i\theta'|_E = q_i$ for all i, so $\mu(G'\theta') < \mu(G, \theta)$. By the induction assumption there is an H such that $G' \xrightarrow{*} H$ with $\theta_H \leq_E \theta'[Var(G')]$. This implies that $G \xrightarrow{*} H$. Also, $\theta_H \leq_E \theta'[Var(G)]$, since the variables of G are a subset of the variables of G'. Since $G\theta' = G\theta$, we know that $\theta_H \leq_E \theta[Var(G)]$.

Case 2 Now suppose that the rule at the root of the proof tree of $E \vdash u\theta \approx v\theta$ is an application of Congruence. There are two cases here: u is a variable or u is not a variable.

Case 2A First we will consider the case where u is not a variable. Then $u = f(u_1, \cdots, u_n)$, $v = f(v_1, \cdots, v_n)$ and $E \vdash u_i\theta \approx v_i\theta$ for all i. There is an application of Decomposition that can be applied to $u \approx v$, resulting in the new goal $G' = \{u_1 \approx v_1, \cdots, u_n \approx v_n\} \cup G_1$. Then $|u_i\theta \approx v_i\theta|_E < |u\theta \approx v\theta|$ for all i, so $\mu(G', \theta) < \mu(G, \theta)$. By the induction assumption there is an H such that $G' \xrightarrow{*} H$ with $\theta_H \leq_E \theta[Var(G')]$. This implies that $G \xrightarrow{*} H$ and $\theta_H \leq_E \theta[Var(G)]$.

Case 2B: Now we consider the final case, where u is a variable and the rule at the root of the proof tree of $E \vdash u\theta \approx v\theta$ is an application of Congruence. Let $u\theta = f(u_1, \cdots, u_n)$. Then, for each i, $E \vdash u_i \approx v_i\theta$, and $|u_i \approx v_i\theta|_E < |u\theta \approx v\theta|_E$. There is an application of Variable Decomposition that can be applied to $u \approx v$, resulting in the new goal $G' = \{u \approx f(x_1, \cdots, x_n)\} \cup (\{x_1 \approx v_1, \cdots, x_n \approx v_n\} \cup G_1)[u \mapsto f(x_1, \cdots, x_n)]$. Let θ' be the substitution $\theta \cup [x_1 \mapsto u_1, \cdots, x_n \mapsto u_n]$. Then $u \approx f(x_1, \cdots, x_n)$ is solved in G'. Also $|x_i\theta' \approx v_i\theta'|_E < |u\theta \approx v\theta|_E$ for all i. Therefore $\mu(G, \theta) < \mu(G', \theta')$. By the induction assumption there is an H such that $G' \xrightarrow{*} H$ with $\theta_H \leq_E \theta'[Var(G')]$. This implies that $G \xrightarrow{*} H$. Also, $\theta_H \leq_E \theta'[Var(G)]$, since the variables of G are a subset of the variables of G'. Since $G\theta' = G\theta$, we know that $\theta_H \leq_E \theta[Var(G)]$.

□

The fact that we required θ to be ground in the theorem does not limit our results. This implies that any substitution will work

Corollary 1. *Suppose that E is an equational theory, G is a set of goal equations, and θ is any substitution. If $E \models G\theta$ then there exists a goal H such that $G \xrightarrow{*} H$ and $\theta_H \leq_E \theta[Var(G)]$.*

Proof. Let θ' be a skolemized version of θ, i.e., θ' is the same as θ except that every variable in the range of θ is replaced by a new constant. Then θ' is ground, so by Theorem 3 there exists a goal H such that $G \xrightarrow{*} H$ and $\theta_H \leq_E \theta'[Var(G)]$. Then θ_H cannot contain any of the new constants, so $\theta_H \leq_E \theta[Var(G)]$. □

9 *E*-Unification for Syntactic Theories

In this section we will show how we can restrict our inference rules further to get a set of inference rules that resembles the Syntactic Mutation rules of Kirchner. Then we prove that that set of inference rules is complete for syntactic theories.

The definition of a syntactic theory is in terms of equational proofs. The definition of a proof is as follows.

Definition 2. *An* equational proof of $u \approx v$ from E *is a sequence* $u_0 \approx u_1 \approx u_w \approx \cdots \approx u_n$, *for* $n \geq 0$ *such that* $u_0 = u$, $u_n = v$ *and for all* $i \geq 0$, $u_i = u_i[s\theta]$ *and* $u_{i+1} = u_i[t\theta]$ *for some* $s \approx t \in E$ *and some substitution* θ.

Now we give Kirchner's definition of *syntactic theory.*

Definition 3. *An equational theory E is* resolvent *if every equation $u \approx v$ with $E \models u \approx v$ has an equational proof such that there is at most one step at the root. A theory is* syntactic *if it has an equivalent finite resolvent presentation.*

From now on, when we discuss a Syntactic Theory E, we will assume that E is the resolvent presentation of that theory.

In this paper, we are considering bottom-up proofs instead of equational replacement proofs. We will call a bottom-up proof *resolvent* if whenever an equation appears as a result of Equation Application, then its left and right children must have appeared as a result of an application of Congruence at the root. We will call E *bottom-up resolvent* if every ground equation $u \approx v$ implied by E has a bottom-up resolvent proof. Now we show that the definition of resolvent for equational proofs is equivalent to the definition of resolvent for bottom-up proofs.

Theorem 4. *E is resolvent if and only if E is bottom-up resolvent.*

Proof. We need to show how to transform a resolvent equational proof into a resolvent bottom-up proof and vice versa.

Case 1: First consider transforming a resolvent equational proof into a resolvent bottom-up proof. We will prove this can be done by induction on the the lexicographic combination of the number of steps in the equational proof and the number of symbols appearing in the equation.

Case 1A: Suppose $u \approx v$ has an equational proof with no steps at the root. Then $u \approx v$ is of the form $f(u_1, \cdots, u_n) \approx f(v_1, \cdots, v_n)$, and there are equational proofs of $u_i \approx v_i$ for all i. Since each equation $u_i \approx v_i$ has fewer symbols than $u \approx v$ and does not have a longer proof, then, by the induction argument there is a resolvent bottom-up proof of each $u_i \approx v_i$, and by adding one more congruence step to all the $u_i \approx v_i$, we get a resolvent bottom-up proof of $u \approx v$.

Case 1B: Now suppose $u \approx v$ has an equational proof with one step at the root. Then there is a ground instance $s \approx t$ of something in E such that the proof of $u \approx v$ is a proof of $u \approx s$ with no steps at the top, followed by a replacement of s with t, followed by a proof of $t \approx v$ with no steps at the root. By induction, each child in the proof of $u \approx s$ has a resolvent bottom-up proof. Therefore $u \approx s$ has a resolvent bottom-up proof with a Congruence step at the root. Similarly, $t \approx v$ has a resolvent bottom-up proof with a Congruence step at the root. If we apply Equation Application to those two proofs, we get a bottom-up resolvent proof of $u \approx v$.

Case 2: Now we will transform a resolvent bottom-up proof of $u \approx v$ to an equational proof of $u \approx v$, by induction on $|u \approx v|_E$.

Case 2A: Suppose $u \approx v$ has a bottom-up resolvent proof with an application of Congruence at the root. Then $u \approx v$ is of the form $f(u_1, \cdots, u_n) \approx f(v_1, \cdots, v_n)$, and there are bottom-up resolvent proofs of $u_i \approx v_i$ for all i. Since each equational proof of $u_i \approx v_i$ is shorter than the proof of $u \approx v$, then, by the induction argument there is a resolvent equational proof of each $u_i \approx v_i$, and they can be combined to give a resolvent equational proof of $u \approx v$.

Case 2B: Now suppose $u \approx v$ has a resolvent bottom-up proof with one Equation Application step at the root. Then there is some $s \approx t$ in E such that the proof of $u \approx v$ is a proof of $u \approx s$ with a Congruence step at the root, and a proof of $t \approx v$ with a Congruence step at the root, then an Equation Application using the equation $s \approx t$ from E. By induction, the corresponding equalities of subterms of $u \approx s$ have resolvent equational proofs. So $u \approx s$ has a resolvent equational proof with no steps at the root. Similarly, $t \approx v$ also has a resolvent equational proof with no steps at the root. So $u \approx v$ has a resolvent equational proof with one step at the root.

$\square$

Now we give the inference rules for solving E-unification problems in Syntactic Theories. The rules for Decomposition and Variable Decomposition remain the same, but Mutate becomes more restrictive. We replace Mutate and Variable Mutate with one rule that covers several cases.

Mutate

$$\frac{\{u \approx v\} \cup G}{\{Dec(u \approx s), Dec(v \approx t)\} \cup G}$$

where $u \approx v$ is selected in the goal, $s \approx t \in E$, v is not a variable, if both u and s are not variables then they have the same root symbol, and if t is not a variable then v and t have the same root symbol. We also introduce a function Dec, which when applied to an equation indicates that the equation should be decomposed eagerly according to the following rules:

$$\frac{\{Dec(f(u_1, \cdots, u_n) \approx f(s_1, \cdots, s_n))\} \cup G}{\{u_1 \approx s_1, \cdots, u_n \approx s_n\} \cup G}$$

$$\frac{\{Dec(x \approx f(s_1, \cdots, s_n))\} \cup G}{\{x \approx f(x_1, \cdots, x_n)\} \cup G[x \mapsto f(x_1, \cdots, x_n)] \cup \{x_1 \approx s_1, \cdots, x_n \approx s_n\}}$$

where the x_i are fresh variables.

$$\frac{\{Dec(x \approx y)\} \cup G}{\{x \approx y\} \cup G}$$

$$\frac{\{Dec(f(s_1, \cdots, s_n) \approx x)\} \cup G}{G[x \mapsto f(x_1, \cdots, x_n)] \cup \{x_1 \approx s_1, \cdots, x_n \approx s_n\}}$$

where the x_i are fresh variables.

Now we prove a completeness theorem for this new set of inference rules, which is Decomposition, Variable Decomposition, and the Mutate rule given above.

Theorem 5. *Suppose that E is a resolvent presentation of an equational theory, G is a set of goal equations, and θ is a ground substitution. If $E \models G\theta$ then there exists a goal H in normal form such that $G \xrightarrow{*} H$ and $\theta_H \leq_E \theta[Var(G)]$.*

Proof. The proof is the same as the proof of Theorem 3, except for Case 1. In this case, we can show that one of the forms of the Mutate rules from this section is applicable. Here, instead of using Lemma 5 to say that an Equation Application must have a Congruence as a right child, we instead use the definition of bottom-up resolvent to say that an Equation Application has a Congruence as both children. The full proof is in [13]. □

10 Conclusion

We have given a new goal-directed inference system for E-unification. We are interested in goal-directed E-unification for two reasons. One is that many other inferences systems for which E-unification would be useful are goal directed, and so a goal-directed inference system will be easier to combine with other inference systems. The second reason is that we believe this particular inference system is such that we can use it to find some decidable classes of equational theories for E-unification and analyze their complexity. We have already made progress in this direction in [14, 15].

Our inference system is an improvement over the inference systems BT of [4] and **Trans** of [5] for Equational Unification. There are two important differences between our inference system an those other two. The first is that those inference systems require the Variable Elimination rule. This blows up the search space, because, for an equation $x \approx t$, both Variable Elimination and (Root) Imitation will be applicable. We do not require Variable Elimination. The second difference is that both of those inference systems require an inference with a variable in the goal. In BT, Root Rewriting inferences are performed on variable-variable pairs. This blows up the search space, because everything unifies with a variable. Similarly, in BT, Root Imitation inferences are performed on variable-variable pairs. That blows up the search space because it must be attempted for every function symbol and constant. In **Trans**, there is a rule called Paramodulation at Variable Occurence. This is like a Mutate (Lazy Paramodulation) inference applied to a variable x in a goal equation $x \approx t$. Again, every equation will unify with x, so the search space will blow up. Gallier and Snyder recognize the above-mentioned problems of $\mathcal{BT}$. There solution is to create another inference system called $\mathcal{T}$, but that one is different because Root Rewriting inferences are now allowed at non-root positions.

The inference system we have given is similar to the Syntactic Mutation inference system of [9]. The difference is that our inference system can be applied to all equational theories, not just Syntactic Theories as in their case. Also, we show how our results are easily adapted to give an inference similar to the Syntactic Mutation rules of [9]. While the rules in [9] have not been proved complete, we prove that ours are complete.

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