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1 Equational Unification

In the following let E be a set of identities of the form $\{e_1 \approx f_1, \dots, e_n \approx f_n\}$. Furthermore let $Sig(E)$ denote the set of all function symbols occurring in E . Let Σ be a finite set of function symbols and a superset of $Sig(E)$.

Definition 1.1. An E -unification problem over Σ is a finite set S of the form $S = \left\{ s_1 \stackrel{?}{\approx}_E t_1, \dots, s_n \stackrel{?}{\approx}_E t_n \right\}$ with $s_1, \dots, s_n, t_1, \dots, t_n \in T(\Sigma, V)$, V being a countable set of Variables.

A substitution σ is an E -unifier of S iff $\sigma(s_i) \approx_E \sigma(t_i)$ for all $1 \leq i \leq n$. The set of all E -unifiers of S is denoted by $\mathcal{U}_E(S)$. S is E -unifiable iff $\mathcal{U}_E(S) \neq \emptyset$.

Definition 1.2. Let S be an E -unification problem over Σ .

- S is an **elementary** E -unification problem iff $Sig(E) = \Sigma$.
- S is an E -unification problem **with constants** iff $\Sigma - Sig(E) \subseteq \Sigma^{(0)}$ and $Sig(E) \subset \Sigma$
- S is an **general** E -unification problem iff $\Sigma - Sig(E)$ contains an at least unary function symbol.

One *most general unifier* does not always suffice to represent $\mathcal{U}_E(S)$. In this case we need a *minimal complete set of unifiers* but to define this set we first need an order on substitutions.

Definition 1.3. Let X be a set of variables. A substitution σ is **more general** modulo \approx_E than a substitution σ' on X iff there is a substitution δ such that $\delta(\sigma(x)) \approx_E \sigma'(x)$ for all $x \in X$. We denote this by $\sigma \lesssim_E^X \sigma'$.

\lesssim_E^X is a quasi order since it obviously is reflexive and transitive. But why do we only demand equality modulo \approx_E on X and not on all Variables like we did in syntactic unification? Note that by the restriction to Variables in X more substitutions are comparable with respect to \lesssim_E^X since we do not demand equality modulo \approx_E on all Variables. Lets denote the Variables occurring in an E -unification problem S by $\mathcal{Var}(S)$. It is easy to see that if $X = \mathcal{Var}(S)$, σ' is an E -unifier of S and $\sigma \lesssim_E^X \sigma'$ then σ is also an E -unifier of S . This only shows that restriction to X does not do any damage but the reason it is useful is that there are E -unification problems S for which any *minimal complete set of E-unifiers* has to contain Variables not occurring in S . Lets consider a small example, let $\sigma := \{x \mapsto f(y)\}$ be in \mathcal{M} a *minimal complete set of E-unifiers* of S with $\mathcal{Var}(S) = \{x\}$ and $\{a \approx x\} \notin E$. Clearly $\sigma' := \{x \mapsto f(a)\}$ is also an E -unifier of S but σ and σ' are incomparable w.r.t. $\lesssim_E^{\{x,y\}}$. The substitution $\delta := \{y \mapsto a\}$ does not work here since $\delta(\sigma(y)) = a \not\approx_E y = \sigma'(y)$ which means there has to be another unifier σ'' in \mathcal{M} with $\sigma'' \lesssim_E^{\{x,y\}} \sigma$. But if we restrict X to $\{x\}$ we only need that $\delta(\sigma(x)) = f(a) \approx_E f(a) = \sigma'(x)$ so $\sigma \lesssim_E^{\{x\}} \sigma'$ holds. We see that *minimal complete sets of E-unifiers* can become unnecessary large if we consider all Variables. Since we have talked about these sets a lot lets define them formally.

Definition 1.4. Let S be an E -unification problem over Σ and let $X := \text{Var}(S)$. An **E -complete** set of S is a set of substitutions \mathcal{C} that satisfies the following properties.

- each $\sigma \in \mathcal{C}$ is an E -unifier of S
- for all $\theta \in \mathcal{U}_E(S)$ there exists a $\sigma \in \mathcal{C}$ such that $\sigma \lesssim_E^X \theta$

An **E -minimal E -complete** set is an E -complete set \mathcal{M} that satisfies the additional property

- for all $\sigma, \sigma' \in \mathcal{M}$, $\sigma \lesssim_E^X \sigma'$ implies $\sigma = \sigma'$.

The substitution σ is a **most general E -unifier** (mgu) of S iff $\{\sigma\}$ is an E -minimal E -complete set of S .

Now let us consider an example in which an E -minimal E -complete set contains infinitely many elements. Let $A := \{x + (y + z) \approx (x + y) + z\}$ be a set of identities and $S := \left\{x + a \overset{?}{\approx}_A a + x\right\}$ an A -unification problem over $\Sigma := \{+, a\}$. For $n > 0$, we define substitutions σ_n inductively as follows:

$$\begin{aligned}\sigma_1 &:= \{x \mapsto a\} \\ \sigma_{n+1} &:= \{x \mapsto a + \sigma_n(x)\}\end{aligned}$$

Since A axiomatizes associativity we can omit the brackets and give an explicit definition of σ_n .

$$\sigma_n := \underbrace{\{a + \cdots + a\}}_{n \times a}$$

Now it is easy to see that all σ_n are A -unifiers of S . Lets consider an arbitrary A -unifier θ of S . $\theta(x)$ has the form $\theta(x) := x_1 + \cdots + x_n$ where the x_i 's are either a or a variable. Since θ is an A -unifier of S we have that:

$$\begin{aligned}\theta(x) + a &\approx_A a + \theta(x) \\ x_1 + \cdots + x_n + a &\approx_A a + x_1 + \cdots + x_n \\ \implies x_1 = a, x_n = a &\quad a + x_2 + \cdots + x_{n-1} + a + a \approx_A a + a + x_2 + \cdots + x_{n-1} + a \\ \implies x_2 = a, x_{n-1} = a &\quad a + a + \cdots + a + a + a \approx_A a + a + a + \cdots + a + a \\ \vdots &\quad \vdots \\ \implies &\quad \underbrace{a + \cdots + a}_{n+1 \times a} \approx_A \underbrace{a + \cdots + a}_{n+1 \times a}\end{aligned}$$

So $\theta(x) = \sigma_n(x)$ which implies $\sigma \lesssim_A^{\{x\}} \theta$. Since we picked θ arbitrarily this yields A -completeness of the set $\mathcal{M} := \bigcup_{n>0} \{\sigma_n\}$. All σ_n are distinct and map x to ground terms. Hence they are pairwise incomparable with respect to $\lesssim_A^{\{x\}}$. This yields A -minimality of \mathcal{M} . We see that E -minimal E -complete sets do not

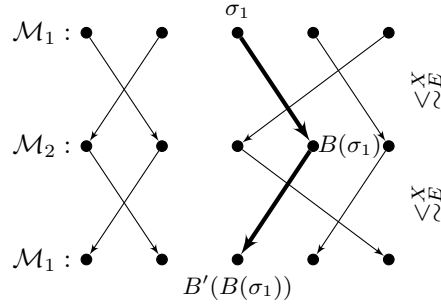
need to have finite cardinality.

We denote equivalence class induced by \lesssim_E^X with \sim_E^X .

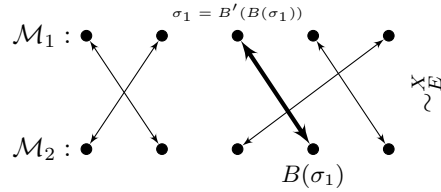
$$\sigma \sim_E^X \sigma' \text{ iff } \sigma \lesssim_E^X \sigma' \text{ and } \sigma' \lesssim_E^X \sigma$$

Lemma 1.5. *Let \mathcal{M}_1 and \mathcal{M}_2 be E -minimal E -complete sets of S . Then there exists a bijective mapping $B : \mathcal{M}_1 \mapsto \mathcal{M}_2$ such that $\sigma_1 \sim_E^X B(\sigma_1)$ for all $\sigma_1 \in \mathcal{M}_1$.*

Proof. We define a mapping $B : \mathcal{M}_1 \mapsto \mathcal{M}_2$ such that $B(\sigma_1) \lesssim_E^X \sigma_1$ for all $\sigma_1 \in \mathcal{M}_1$. This is possible since $\mathcal{M}_1 \subseteq \mathcal{U}_E(S)$ and E -completeness of \mathcal{M}_2 yields that for every $\sigma_1 \in \mathcal{M}_1$ there exists a $\sigma_2 \in \mathcal{M}_2$ such that $\sigma_2 \lesssim_E^X \sigma_1$. We define $B' : \mathcal{M}_2 \mapsto \mathcal{M}_1$ in a similar way.



Since by definition $B'(B(\sigma_1)) \lesssim_E^X B(\sigma_1) \lesssim_E^X \sigma_1$ E -minimality of \mathcal{M}_1 implies that $B'(B(\sigma_1)) = \sigma_1$ for all $\sigma_1 \in \mathcal{M}_1$. Symmetrically, $B(B'(\sigma_2)) = \sigma_2$ for all $\sigma_2 \in \mathcal{M}_2$. It follows that B is a bijection and $B' = B^{-1}$.



□

The most interesting consequence from this Lemma is that E -minimal E -complete sets of the same S always have the same cardinality. This allows us to classify equational theories \approx_E by the existence and possible cardinalities of E -minimal E -complete sets of E -unification problems.

Definition 1.6. The equational theory \approx_E is of **unification type**

unitary iff for all E -unification problems S there exists an E -minimal E -complete set of cardinality ≤ 1 .

finitary iff for all E -unification problems S there exists an E -minimal E -complete set with finite cardinality.

infinitary iff for all E -unification problems S there exists an E -minimal E -complete set, and there exists an E -unification problem for which this set is infinite.

zero iff there exists an E -unification problem that does not have an E -minimal E -complete set.

Note that if the E -unification problem S has no E -unifiers then the empty set is an E -minimal E -complete set of S . \emptyset is E -complete because there are no $\sigma \in \emptyset$ and \mathcal{U}_E is empty. E -minimality holds trivially. This is the reason we allow the cardinalities 0 and 1 in the *unitary* case. An example for a *finitary* theory that is not *unitary* is $\mathcal{C} := \{f(x, y) \approx f(y, x)\}$ which axiomatizes commutativity. With $\mathcal{A} := \{x + (y + z) \approx (x + y) + z\}$ the theory that axiomatizes associativity we have already seen an example for an *infinitary* equational theory. In the definition of the *unification types* we allowed for arbitrary E -unification problems but if we distinguish between elementary E -unification problems, E -unification problems with constants and general E -unification problems we might end up with different *unification types*. For example

2 Boolean Rings