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# Anti-Pattern Matching Modulo

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**Abstract.** Negation is intrinsic to human thinking and most of the time when searching for something, we base our patterns on both positive and negative conditions. In a recent work, the notion of term was extended to the one of anti-term, *i.e.* terms that may contain complement symbols. Here we generalize the syntactic anti-pattern matching to anti-pattern matching *modulo* an arbitrary equational theory  $\mathcal{E}$ , and we study the specific and practically very useful case of associativity, possibly with a unity ( $\mathcal{AU}$ ). To this end, based on the *syntacticness* of associativity, we present a rule-based associative matching algorithm, and we extend it to  $\mathcal{AU}$ . This algorithm is then used to solve  $\mathcal{AU}$  anti-pattern matching problems. This allows us to be generic enough so that for instance, the *AllDiff* standard predicate of constraint programming becomes simply expressible in this framework.  $\mathcal{AU}$  anti-patterns are implemented in the TOM language and we show some examples of their usage.

## 1 Introduction

When searching for something, we usually base our searches on both positive and negative conditions. Indeed, when stating “except a red car”, it means that whatever the other characteristics are, a *red car* will not be accepted. This is a very common way of thinking, more natural than a series of disjunctions like “a white car *or* a blue one *or* a black one *or* ...”.

Anti-patterns were introduced in [15] in order to provide a compact and expressive representation for sets of terms. Just by properly placing complement symbols in a pattern, a nice expressivity can be obtained, which can spare the user of using more complex and harder to read constructions (like disjunctions for instance). Syntactic anti-patterns (*i.e.* when operators have no particular property) are very useful, but the anti-patterns are even more valuable when associated with equational theories, in particular with associativity, unit, and eventually with commutativity. For instance, consider the associative matching with neutral element as provided by TOM (<http://tom.loria.fr>) — a programming language that extends C and Java with algebraic data-types, pattern matching and strategic rewriting facilities [2]. The pattern  $list(*, \neg a, *)$  denotes a list which contains at least one element different from the constant  $a$ , whereas  $\neg list(*, a, *)$  denotes a list which does not contain any  $a$  (*list* is an associative

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operator having the empty list as its neutral element, and  $*$  denotes any sub-list). By using non-linearity we can express, in a single pattern, list constraints as *AllDiff* or *AllEqual*. Take for instance the pattern  $list(*, x, *, x, *)$  that denotes a list with at least two equal elements ( $x$  is a variable). The complement of this,  $\neg list(*, x, *, x, *)$  matches lists that have only distinct elements, *i.e.* *AllDiff*. In a similar way, as  $list(*, x, *, \neg x, *)$  matches the lists that have at least two distinct elements, its complement  $\neg list(*, x, *, \neg x, *)$  denotes any list whose elements are all equal. Without anti-patterns, these constructions would have to be expressed as loops, disjunctions *etc.* Of course that instead of the constant  $a$  or the variable  $x$ , we could have used any complex pattern or anti-pattern.

After presenting some general notions in Section 2, our first contribution, in Section 3, is to solve associative matching problems using a rule-based algorithm. We further adapt it to also support neutral elements. A second main contribution is to provide, in Section 4, an anti-pattern matching algorithm for an arbitrary equational theory, provided that a finitary matching algorithm is available for the given theory. We show how an equational anti-pattern matching problem can be transformed into a finite subset of equivalent equational problems. We then focus on the associative anti-patterns with neutral elements and we present a practical and efficient algorithm for solving such problems. In Section 5 we show how they are integrated in the TOM language.

Although we will make precise our main notations, we assume that the reader is familiar with the standard notions of algebraic rewrite systems, for example presented in [1] and rule-based unification algorithms, see *e.g.* [12].

## 2 Terms and anti-patterns

*Terms and equality.* A signature  $\mathcal{F}$  is a set of function symbols, each one having a fixed arity associated to it.  $\mathcal{T}(\mathcal{F}, \mathcal{X})$  is the set of *terms* built from a given finite set  $\mathcal{F}$  of function symbols where constants are denoted  $a, b, c, \dots$ , and a denumerable set  $\mathcal{X}$  of variables denoted  $x, y, z, \dots$ . A term  $t$  is said to be *linear* if no variable occurs more than once in  $t$ . The set of variables occurring in a term  $t$  is denoted by  $\mathcal{V}ar(t)$ . If  $\mathcal{V}ar(t)$  is empty,  $t$  is called a *ground term* and  $\mathcal{T}(\mathcal{F})$  is the set of ground terms.

A *substitution*  $\sigma$  is an assignment from  $\mathcal{X}$  to  $\mathcal{T}(\mathcal{F}, \mathcal{X})$ , denoted  $\sigma = \{x_1 \mapsto t_1, \dots, x_k \mapsto t_k\}$  when its domain  $\text{Dom}(\sigma)$  is finite. Its application, written  $\sigma(t)$ , is defined by  $\sigma(x_i) = t_i$ ,  $\sigma(f(t_1, \dots, t_n)) = f(\sigma(t_1), \dots, \sigma(t_n))$  for  $f \in \mathcal{F}$ , and  $\sigma(y) = y$  if  $y \notin \text{Dom}(\sigma)$ . Given a term  $t$ ,  $\sigma$  is called a *grounding substitution* for  $t$  if  $\sigma(t) \in \mathcal{T}(\mathcal{F})$ <sup>1</sup>. The set of substitutions is denoted  $\Sigma$ . The set of grounding substitutions for a term  $t$  is denoted  $\mathcal{GS}(t)$ .

The ground semantics of a term  $t \in \mathcal{T}(\mathcal{F}, \mathcal{X})$  is the set of all its ground instances:  $\llbracket t \rrbracket_g = \{\sigma(t) \mid \sigma \in \mathcal{GS}(t)\}$ . In particular,  $\llbracket x \rrbracket_g = \mathcal{T}(\mathcal{F})$ .

A *position* in a term is a finite sequence of natural numbers. The subterm  $u$  of a term  $t$  at position  $\omega$  is denoted  $t|_\omega$ , where  $\omega$  describes the path from the root of  $t$  to the root of  $u$ .  $t(\omega)$  denotes the root symbol of  $t|_\omega$ . By  $t[u]_\omega$  we express

<sup>1</sup> usually different from a *ground* substitution, which does not depend on  $t$ .

that the term  $t$  contains  $u$  as subterm at position  $\omega$ . Positions are ordered in the classical way:  $\omega_1 < \omega_2$  if  $\omega_1$  is a prefix of  $\omega_2$ .

For an equational theory  $\mathcal{E}$ , an  $\mathcal{E}$ -*matching equation* (*matching equation* for short) is of the form  $p \prec_{\mathcal{E}} t$  where  $p$  is a term classically called a pattern and  $t$  is a term, generally considered as ground. The substitution  $\sigma$  is an  $\mathcal{E}$ -*solution of the  $\mathcal{E}$ -matching equation*  $p \prec_{\mathcal{E}} t$  if  $\sigma(p) =_{\mathcal{E}} t$ , and it is called an  $\mathcal{E}$ -*match* from  $p$  to  $t$ .

An  $\mathcal{E}$ -*matching system*  $S$  is a possibly existentially quantified conjunction of matching equations:  $\exists \bar{x} (\wedge_i p_i \prec_{\mathcal{E}} t_i)$ . A substitution  $\sigma$  is an  $\mathcal{E}$ -*solution* of such a matching system if there exists a substitution  $\rho$ , with domain  $\bar{x}$ , such that  $\sigma$  is solution of all the matching equations  $\rho(p_i) \prec_{\mathcal{E}} \rho(t_i)$ . The set of solutions of  $S$  is denoted by  $Sol_{\mathcal{E}}(S)$ .

An  $\mathcal{E}$ -*matching disjunction*  $D$  is a disjunction of  $\mathcal{E}$ -matching systems. Its solutions are the substitutions solution of at least one of its system constituents. Its free variables  $\mathcal{FVar}(D)$  are defined as usual in predicate logic. We use the notation  $D[S]$  to denote that the system  $S$  occurs in the *context*  $D$ .

Given an equational theory  $\mathcal{E}$  and two sets  $A$  and  $B$ , we consider as usual that:  $t \in_{\mathcal{E}} A \Leftrightarrow \exists t' \in A$  such that  $t =_{\mathcal{E}} t'$ ;  $A \subseteq_{\mathcal{E}} B \Leftrightarrow \forall t \in A$  we have  $t \in_{\mathcal{E}} B$ ;  $A =_{\mathcal{E}} B \Leftrightarrow A \subseteq_{\mathcal{E}} B$  and  $B \subseteq_{\mathcal{E}} A$ .

A binary operator  $f$  is called *associative* if it satisfies the equational axiom  $\forall x, y, z \in \mathcal{T}(\mathcal{F}, \mathcal{X}) : f(f(x, y), z) = f(x, f(y, z))$  and *commutative* if  $\forall x, y \in \mathcal{T}(\mathcal{F}, \mathcal{X}) : f(x, y) = f(y, x)$ . A binary operator can have neutral elements — symbols of arity zero:  $e_f$  is a *left neutral* operator for  $f$  if  $\forall x \in \mathcal{T}(\mathcal{F}, \mathcal{X}), f(e_f, x) = x$ ;  $e_f$  is a *right neutral* operator for  $f$  if  $\forall x \in \mathcal{T}(\mathcal{F}, \mathcal{X}), f(x, e_f) = x$ ;  $e_f$  is a *neutral* or *unit* operator for  $f$  if it is a left and right neutral operator for  $f$ . When  $f$  is associative or associative with a unit, this is denoted  $\mathcal{A}$  or  $\mathcal{AU}$  respectively.

*Anti-terms.* An anti-term [15] is a term that may contain complement symbols, denoted by  $\neg$ . The BNF of anti-terms is:

$$\mathcal{AT} ::= \mathcal{X} \mid f(\mathcal{AT}, \dots, \mathcal{AT}) \mid \neg \mathcal{AT}, \text{ where } f \text{ respects its arity.}$$

The set of anti-terms (resp. ground anti-terms) is denoted  $\mathcal{AT}(\mathcal{F}, \mathcal{X})$  (resp.  $\mathcal{AT}(\mathcal{F})$ ). Any term is an anti-term, *i.e.*  $\mathcal{T}(\mathcal{F}, \mathcal{X}) \subset \mathcal{AT}(\mathcal{F}, \mathcal{X})$ .

The free variables of an anti-term  $t$  are denoted  $\mathcal{FVar}(t)$ , and the non-free ones  $\mathcal{NFVar}(t)$ . Intuitively, a variable is free if it is not under a  $\neg$ . Typically,  $\mathcal{FVar}(\neg t) = \emptyset$  and  $\mathcal{FVar}(f(x, \neg x)) = \{x\}$ .

The substitutions are only active on free variables. For anti-terms, a ground substitution is a substitution that instantiates all the free variables by ground terms. As detailed in [15], the *ground semantics* is defined as follows:

**Definition 2.1.** *Given an anti-pattern  $q \in \mathcal{AT}(\mathcal{F}, \mathcal{X})$ , the ground semantics is defined by:*

$$\llbracket q[\neg q']_{\omega} \rrbracket_g = \llbracket q[z]_{\omega} \rrbracket_g \setminus \llbracket q[q']_{\omega} \rrbracket_g$$

where  $z$  is a fresh variable and for all  $\omega' < \omega$ ,  $q(\omega') \neq \neg$ .

As stressed in [15], the last condition is essential as it prevents abstracting subterms in a complemented context. This would lead to counter-intuitive situations.

*Example 2.1.*

1.  $\llbracket h(a, \neg b) \rrbracket_g = \llbracket h(a, z) \rrbracket_g \setminus \llbracket h(a, b) \rrbracket_g = \{h(a, \sigma(z)) \mid \sigma \in \mathcal{GS}(h(a, z))\} \setminus \{h(a, b)\}$
2. We can express that we are looking for something that is either not rooted by  $g$ , or it is  $g(a)$ :
 
$$\begin{aligned} \llbracket \neg g(\neg a) \rrbracket_g &= \llbracket z \rrbracket_g \setminus \llbracket g(\neg a) \rrbracket_g = \llbracket z \rrbracket_g \setminus (\llbracket g(z') \rrbracket_g \setminus \llbracket g(a) \rrbracket_g) \\ &= \mathcal{T}(\mathcal{F}) \setminus (\llbracket g(z') \rrbracket_g \setminus \{g(a)\}) \\ &= \mathcal{T}(\mathcal{F}) \setminus (\{g(\sigma(z')) \mid \sigma \in \mathcal{GS}(g(z'))\} \setminus \{g(a)\}) \\ &= \mathcal{T}(\mathcal{F}) \setminus \{g(z) \mid z \in \mathcal{T}(\mathcal{F}, \mathcal{X})\} \cup \{g(a)\}, \end{aligned}$$
3. Non-linearity is crucial to denote any term except those rooted by  $h$  with identical subterms:
 
$$\llbracket \neg h(x, x) \rrbracket_g = \llbracket z \rrbracket_g \setminus \llbracket h(x, x) \rrbracket_g = \mathcal{T}(\mathcal{F}) \setminus \{h(\sigma(x), \sigma(x)) \mid \sigma \in \mathcal{GS}(h(x, x))\}$$

The anti-terms are also called anti-patterns, in particular when they appear in the left-hand side of a match equation. The notions of matching equations, systems and disjunctions are extended to anti-patterns by allowing the *left-hand side* of match equations to be anti-patterns. When a match equation contains anti-patterns, we often refer to it as an *anti-pattern matching equation*. The solutions of such problems are defined later.

### 3 Associative matching

To provide an equational anti-matching algorithm in the next section, we first need to make precise the matching algorithm that serves us as a starting point. The rule-based presentation of an  $\mathcal{AU}$  matching algorithm is also the first contribution of this paper.

As opposed to syntactic matching, matching modulo an equational theory is undecidable as well as not unitary in general [5]. When decidable, matching problems can be quite expensive either to decide matchability or to enumerate complete sets of matchers. For instance, matchability is NP-complete for  $\mathcal{AU}$  or  $\mathcal{AI}$  (idempotency) [3]. Also, counting the number of minimal complete set of matches modulo  $\mathcal{A}$  or  $\mathcal{AU}$  is #P-complete [10].

In this section we focus on the particular useful case of matching modulo  $\mathcal{A}$  and  $\mathcal{AU}$ . The reason why we chose to detail these specific theories are their tremendous usefulness in rule-based programming such as ASF+SDF [4] or MAUDE [8,9] for instance, where lists, and consequently list-matching, are omnipresent.

Since associativity and neutral element are regular axioms (*i.e.* equivalent terms have the same set of variables), we can apply the combination results for matching modulo the union of disjoint regular equational theories [19,21] to get a matching algorithm modulo the theory combination of an arbitrary number of  $\mathcal{A}$ ,  $\mathcal{AU}$  as well as free symbols. Therefore we study in this section matching modulo  $\mathcal{A}$  or  $\mathcal{AU}$  of a single binary symbol  $f$ , whose unit is denoted  $e_f$ . The only other symbols under consideration are free constants. For syntactic matching, a simple rule-based matching algorithm can be found in [7,15].

### 3.1 Matching associative patterns

By making precise this algorithm, our purpose is to provide a simple and intuitive one that can be easily proved to be correct and complete and that will be later adapted to anti-pattern matching<sup>2</sup>. In terms of efficiency, more appropriate solutions were developed in [8,9].

Unification modulo associativity has been extensively studied [20,16]. It is decidable, but infinitary, while  $\mathcal{A}$ -matching is finitary. Our matching algorithm  $\mathcal{A}$ -Matching is described in Figure 1 and is quite reminiscent from [18] although not based on a Prolog resolution strategy. It strongly relies on the *syntacticness* of the associative theory [13,14].

Mutate	$f(p_1, p_2) \ll_{\mathcal{A}} f(t_1, t_2) \iff (p_1 \ll_{\mathcal{A}} t_1 \wedge p_2 \ll_{\mathcal{A}} t_2) \vee$	
	$\exists x(p_2 \ll_{\mathcal{A}} f(x, t_2) \wedge f(p_1, x) \ll_{\mathcal{A}} t_1) \vee$	
	$\exists x(p_1 \ll_{\mathcal{A}} f(t_1, x) \wedge f(x, p_2) \ll_{\mathcal{A}} t_2)$	
SymbolClash <sub>1</sub>	$f(p_1, p_2) \ll_{\mathcal{A}} a \iff \perp$	
SymbolClash <sub>2</sub>	$a \ll_{\mathcal{A}} f(p_1, p_2) \iff \perp$	
ConstantClash	$a \ll_{\mathcal{A}} b \iff \perp$ if $a \neq b$	
Replacement	$z \ll_{\mathcal{A}} t \wedge S \iff z \ll_{\mathcal{A}} t \wedge \{z \mapsto t\}S$ if $z \in \mathcal{FVar}(S)$	
<i>Utility Rules:</i>		
Delete	$p \ll_{\mathcal{A}} p \iff \top$	PropagClash <sub>1</sub> $S \wedge \perp \iff \perp$
Exists <sub>1</sub>	$\exists z(D[z \ll_{\mathcal{A}} t]) \iff D[\top]$ if $z \notin \mathcal{Var}(D[\top])$	PropagClash <sub>2</sub> $S \vee \perp \iff S$
Exists <sub>2</sub>	$\exists z(S_1 \vee S_2) \iff \exists z(S_1) \vee \exists z(S_2)$	PropagSuccess <sub>1</sub> $S \wedge \top \iff S$
DistribAnd	$S_1 \wedge (S_2 \vee S_3) \iff (S_1 \wedge S_2) \vee (S_1 \wedge S_3)$	PropagSuccess <sub>2</sub> $S \vee \top \iff \top$

**Fig. 1.**  $\mathcal{A}$ -Matching:  $p_i$  are patterns,  $t_i$  are ground terms, and  $S$  is any conjunction of matching equations. **Mutate** is the most interesting rule, and it is a direct consequence of the fact that associativity is a *syntactic theory*.  $\wedge, \vee$  are classical boolean connectors.

**Proposition 3.1.** *Given a matching equation  $p \ll_{\mathcal{A}} t$  with  $p \in \mathcal{T}(\mathcal{F}, \mathcal{X})$  and  $t \in \mathcal{T}(\mathcal{F})$ , the application of  $\mathcal{A}$ -Matching always terminates.*

If no solution is lost in the application of a transformation rule, the rule is called *preserving*. It is a *sound* rule if it does not introduce unexpected solutions.

**Proposition 3.2.** *The rules in  $\mathcal{A}$ -Matching are sound and preserving modulo  $\mathcal{A}$ .*

*Proof.* The rule **Mutate** is a direct consequence of the decomposition rules for syntactic theories presented in [14]. The rest of the rules are usual ones for which these results have been obtained for example in [7].  $\square$

**Theorem 3.1.** *Given a matching equation  $p \ll_{\mathcal{A}} t$ , with  $p \in \mathcal{T}(\mathcal{F}, \mathcal{X})$  and  $t \in \mathcal{T}(\mathcal{F})$ , the normal form w.r.t.  $\mathcal{A}$ -Matching exists and it is unique. It can only be of the following types:*

<sup>2</sup> due to the lack of space, lengthy proofs are in appendices

1.  $\top$ , then  $p$  and  $t$  are identical modulo  $\mathcal{A}$ , i.e.  $p =_{\mathcal{A}} t$ ;
2.  $\perp$ , then there is no match from  $p$  to  $t$ ;
3. a disjunction of conjunctions  $\bigvee_{j \in J} (\bigwedge_{i \in I} x_{i_j} \ll_{\mathcal{A}} t_{i_j})$  with  $I, J \neq \emptyset$ , then the substitutions  $\sigma_j = \{x_{i_j} \mapsto t_{i_j}\}_{i \in I, j \in J}$  are all the matches from  $p$  to  $t$ ;

*Example 3.1.* Applying  $\mathcal{A}$ -Matching for  $f \in \mathcal{F}_{\mathcal{A}}$ ,  $x, y \in \mathcal{X}$ , and  $a, b, c, d \in \mathcal{T}(\mathcal{F})$ :

$$\begin{aligned}
& f(x, f(a, y)) \ll_{\mathcal{A}} f(f(b, f(a, c)), d) \\
& \# \Rightarrow \text{Mutate}(x \ll_{\mathcal{A}} f(b, f(a, c)) \wedge f(a, y) \ll_{\mathcal{A}} d) \vee \\
& \exists z(f(a, y) \ll_{\mathcal{A}} f(z, d) \wedge f(x, z) \ll_{\mathcal{A}} f(b, f(a, c))) \vee \\
& \exists z(x \ll_{\mathcal{A}} f(f(b, f(a, c)), z) \wedge f(z, f(a, y)) \ll_{\mathcal{A}} d) \\
& \# \Rightarrow \text{SymbolClash}_1, \text{PropagClash}_2 \exists z(f(a, y) \ll_{\mathcal{A}} f(z, d) \wedge f(x, z) \ll_{\mathcal{A}} f(b, f(a, c))) \\
& \# \Rightarrow \text{Mutate, SymbolClash}_1 \exists z(f(a, y) \ll_{\mathcal{A}} f(z, d) \wedge \\
& ((x \ll_{\mathcal{A}} b \wedge z \ll_{\mathcal{A}} f(a, c)) \vee (x \ll_{\mathcal{A}} f(b, a) \wedge z \ll_{\mathcal{A}} c))) \\
& \# \Rightarrow \text{DistribAnd, Replacement, Mutate, SymbolClash}_{1,2} \exists z(f(a, y) \ll_{\mathcal{A}} f(z, d) \wedge x \ll_{\mathcal{A}} b \wedge z \ll_{\mathcal{A}} \\
& f(a, c)) \# \Rightarrow \text{Replacement, Exists, Mutate, SymbolClash}_{1,2} x \ll_{\mathcal{A}} b \wedge y \ll_{\mathcal{A}} f(c, d).
\end{aligned}$$

### 3.2 Matching associative patterns with unit elements

It is often the case that associative operators have a unit and we know since the early works on *e.g.* OBJ, that this is quite useful from a rule programming point of view. For example, to state *a list L that contains the objects a and b*. This can be expressed by the pattern  $f(x, f(a, f(y, f(b, z))))$ , where  $x, y, z \in \mathcal{X}$ , which will match  $f(c, f(a, f(d, f(b, e))))$  but not  $f(a, b)$  or  $f(c, f(a, b))$ . When  $f$  has for unit  $e_f$ , the previous pattern does match modulo  $\mathcal{AU}$ , producing the substitution  $\{x \mapsto e_f, y \mapsto e_f, z \mapsto e_f\}$  for  $f(a, b)$ , and  $\{x \mapsto c, y \mapsto e_f, z \mapsto e_f\}$  for  $f(c, f(a, b))$ . However,  $\mathcal{A}$  is a theory with a finite equivalence class, which is not the case of  $\mathcal{AU}$ , and an immediate consequence is that the set of matches becomes trivially infinite. For instance,  $\text{Sol}(x \ll_{\mathcal{AU}} a) = \{\{x \mapsto a\}, \{x \mapsto f(e_f, a)\}, \{x \mapsto f(e_f, f(e_f, a))\}, \dots\}$ .

In order to obtain a matching algorithm for  $\mathcal{AU}$ , we replace **SymbolClash** rules in  $\mathcal{A}$ -Matching to appropriately handle unit elements (remember that we assume, because of modularity, that we only have in  $\mathcal{F}$  a single binary  $\mathcal{AU}$  symbol  $f$ , and constants, including  $e_f$ ):

$$\begin{aligned}
\text{SymbolClash}_1^+ \quad f(p_1, p_2) \ll_{\mathcal{AU}} a & \# \Rightarrow (p_1 \ll_{\mathcal{AU}} e_f \wedge p_2 \ll_{\mathcal{AU}} a) \vee \\
& (p_1 \ll_{\mathcal{AU}} a \wedge p_2 \ll_{\mathcal{AU}} e_f) \\
\text{SymbolClash}_2^+ \quad a \ll_{\mathcal{AU}} f(p_1, p_2) & \# \Rightarrow (e_f \ll_{\mathcal{AU}} p_1 \wedge a \ll_{\mathcal{AU}} p_2) \vee \\
& (a \ll_{\mathcal{AU}} p_1 \wedge e_f \ll_{\mathcal{AU}} p_2)
\end{aligned}$$

In addition, we keep all other transformation rules, only changing all match symbols from  $\ll_{\mathcal{A}}$  to  $\ll_{\mathcal{AU}}$ . The new system, named  **$\mathcal{AU}$ -Matching**, is clearly terminating without producing in general a minimal set of solutions. After proving its correctness, we will see what can be done in order to minimize the set of solutions.

**Proposition 3.3.** *The rules of  $\mathcal{AU}$ -Matching are sound and preserving modulo  $\mathcal{AU}$ .*

In order to avoid redundant solutions we further consider that all the terms are in normal form *w.r.t.* the rewrite system  $\mathcal{U} = \{f(e_f, x) \rightarrow x, f(x, e_f) \rightarrow x\}$ . Therefore, we perform a normalized rewriting [17] modulo  $\mathcal{U}$ . This technique ensures that before applying any rule from Figure 1, the terms are in normal forms *w.r.t.*  $\mathcal{U}$ .

## 4 Anti-pattern matching modulo

In [15], anti-patterns were studied in the case of the empty theory. In this section we generalize the matching algorithm to an arbitrary *regular* equational theory  $\mathcal{E}$ , that doesn't contain the symbol  $\neg$ . The presented results allow the use of anti-patterns in a general context, and they constitute the main contributions of the paper.

**Definition 4.1.** *Given an equational theory  $\mathcal{E}$  and  $t \in \mathcal{T}(\mathcal{F})$ , the ground semantics of  $t$  modulo  $\mathcal{E}$  is defined as:*

$$\llbracket t \rrbracket_{g\mathcal{E}} = \{t' \mid t' \in_{\mathcal{E}} \llbracket t \rrbracket_g\}.$$

Therefore, the ground semantics of  $t$  modulo  $\mathcal{E}$  is the set of all the ground terms that can be computed from the ground semantics of  $t$  by applying the axioms of  $\mathcal{E}$ .

**Definition 4.2.** *Given  $q \in \mathcal{AT}(\mathcal{F}, \mathcal{X})$  and a theory  $\mathcal{E}$ , the ground semantics of  $q$  modulo  $\mathcal{E}$  is defined recursively in the following way:*

$$\llbracket q[\neg q']_{\omega} \rrbracket_{g\mathcal{E}} = \begin{cases} \llbracket q[z]_{\omega} \rrbracket_{g\mathcal{E}} \setminus \llbracket q[q']_{\omega} \rrbracket_{g\mathcal{E}}, & \text{if } \mathcal{F}\mathcal{V}\text{ar}(q[\neg q']_{\omega}) = \emptyset \\ \llbracket \sigma(q[\neg q']_{\omega}) \rrbracket_{g\mathcal{E}}, & \text{for all } \sigma \in \mathcal{GS}(q[\neg q']_{\omega}) \end{cases}$$

where  $z$  is a fresh variable and for all  $\omega' < \omega$ ,  $q(\omega') \neq \neg$ .

When  $\mathcal{E}$  is the empty theory, this definition is perfectly compatible with Definition 2.1. However, in the equational case a direct adaptation cannot be used. Consider the pattern  $f(x, f(\neg a, y))$ , where  $f$  is  $\mathcal{AU}$ . This intuitively denotes the lists that contain at least one element different from  $a$ , like  $f(b, f(a, c))$  for instance. Suppose we use Definition 2.1 to compute the ground semantics, we would get  $\llbracket f(x, f(z, y)) \rrbracket_{g\mathcal{AU}} \setminus \llbracket f(x, f(a, y)) \rrbracket_{g\mathcal{AU}}$ , which does not contain the term  $f(b, f(a, c))$ . This happens because giving different values to  $x, y$  and applying the  $\mathcal{AU}$  axioms differently on the two terms, we obtain different term structures in the two sets. But this is not the intuitive semantics of anti-patterns.

*Example 4.1.*

$$\begin{aligned} \llbracket \neg f(x, f(\neg a, y)) \rrbracket_{g\mathcal{AU}} &= \llbracket z \rrbracket_{g\mathcal{AU}} \setminus \llbracket f(x, f(\neg a, y)) \rrbracket_{g\mathcal{AU}} \\ &= \mathcal{T}(\mathcal{F}) \setminus \bigcup_{\sigma} \llbracket f(\sigma(x), f(\neg a, \sigma(y))) \rrbracket_{g\mathcal{AU}} \\ &= \mathcal{T}(\mathcal{F}) \setminus \bigcup_{\sigma} (\llbracket f(\sigma(x), f(z, \sigma(y))) \rrbracket_{g\mathcal{AU}} \setminus \llbracket f(\sigma(x), f(a, \sigma(y))) \rrbracket_{g\mathcal{AU}}) \\ &= \text{everything that is not an f or an f with only a inside} \end{aligned}$$



In the empty theory, given  $q \in \mathcal{AT}(\mathcal{F}, \mathcal{X})$  and  $t \in \mathcal{T}(\mathcal{F})$ , the matching equation  $q \prec t$  has a solution when there exists a substitution  $\sigma$  such that  $t \in \llbracket \sigma(q) \rrbracket_g$ . This is extended to matching modulo  $\mathcal{E}$  as follows:

**Definition 4.3.** For all  $q \in \mathcal{AT}(\mathcal{F}, \mathcal{X})$  and  $t \in \mathcal{T}(\mathcal{F})$ , the solutions of the anti-pattern matching equation  $q \prec_{\mathcal{E}} t$  are:

$$\text{Sol}(q \prec_{\mathcal{E}} t) = \{\sigma \mid t \in \llbracket \sigma(q) \rrbracket_{g_{\mathcal{E}}}, \text{ with } \sigma \in \mathcal{GS}(q)\}.$$

A general anti-pattern matching problem  $P$  is any first-order expression whose atomic formulae are anti-pattern matching equations. To define their solutions, we rely on the usual definition of validity in predicate logic:

**Definition 4.4.** Given an anti-pattern matching problem  $P$ , the solutions modulo  $\mathcal{E}$  are defined as:  $\text{Sol}_{\mathcal{E}}(P) = \{\sigma \mid \models \sigma(P)\}$ , where  $\models q \prec_{\mathcal{E}} t \Leftrightarrow \models t \in \llbracket q \rrbracket_{g_{\mathcal{E}}}$ .

Let us look at several examples of anti-pattern matching modulo in some usual equational theories:

*Example 4.2.* In the syntactic case we have:

- $\text{Sol}(h(\neg a, x) \prec h(b, c)) = \{x \mapsto c\}$ ,
- $\text{Sol}(h(x, \neg g(x)) \prec h(a, g(b))) = \{x \mapsto a\}$ ,
- $\text{Sol}(h(x, \neg g(x)) \prec h(a, g(a))) = \emptyset$ .

In the associative theory:

- $\text{Sol}(f(x, f(\neg a, y)) \prec_{\mathcal{A}} f(b, f(a, f(c, d)))) = \{x \mapsto f(b, a), y \mapsto d\}$ ,
- $\text{Sol}(f(x, f(\neg a, y)) \prec_{\mathcal{A}} f(a, f(a, a))) = \emptyset$ .

The following patterns express that we do not want an  $a$  below  $f$ :

- $\text{Sol}(\neg f(x, f(a, y)) \prec_{\mathcal{A}} f(b, f(a, f(c, d)))) = \emptyset$ ,
- $\text{Sol}(\neg f(x, f(a, y)) \prec_{\mathcal{A}} f(b, f(b, f(c, d)))) = \Sigma$ .

A combination of the two previous examples,  $\neg f(x, f(\neg a, y))$ , would naturally correspond to *an f with only a inside*:

- $\text{Sol}(\neg f(x, f(\neg a, y)) \prec_{\mathcal{A}} f(a, f(b, a))) = \emptyset$ ,
- $\text{Sol}(\neg f(x, f(\neg a, y)) \prec_{\mathcal{A}} f(a, f(a, a))) = \Sigma$ .

Non-linearity can be also useful:  $\text{Sol}(\neg f(x, x) \prec_{\mathcal{A}} f(a, f(b, f(a, b)))) = \emptyset$ , but  $\text{Sol}(\neg f(x, x) \prec_{\mathcal{A}} f(a, f(b, f(a, c)))) = \Sigma$ . If besides associative, we consider that  $f$  is also commutative, we have the following results for matching modulo  $\mathcal{AC}$ :  $\text{Sol}(f(x, f(\neg a, y)) \prec_{\mathcal{AC}} f(a, f(b, c))) = \{\{x \mapsto a, y \mapsto c\}, \{x \mapsto a, y \mapsto b\}, \{x \mapsto b, y \mapsto a\}, \{x \mapsto c, y \mapsto a\}\}$ .

#### 4.1 From anti-pattern matching to equational problems

To solve anti-pattern matching modulo, a solution is to first transform the initial matching problem into an equational one. This is performed using the following transformation rule:

$$\text{ElimAnti } q[\neg q']_{\omega} \prec_{\mathcal{E}} t \mapsto \exists z q[z]_{\omega} \prec_{\mathcal{E}} t \wedge \forall x \in \mathcal{FVar}(q') \text{ not}(q[q']_{\omega} \prec_{\mathcal{E}} t) \\ \text{if if } \forall \omega' < \omega, q(\omega') \neq \neg \text{ and } z \text{ a fresh variable}$$

An anti-pattern matching problem  $P$  not containing any  $\neg$  symbol, is a first-order formula where the symbol *not* is the usual negation of predicate logic, the symbol  $\prec_{\mathcal{E}}$  is interpreted as  $=_{\mathcal{E}}$  and the symbol  $\forall$  is the usual universal quantification:  $\forall xP \equiv \text{not}(\exists x\neg P)$ . Therefore they are exactly  $\mathcal{E}$ -disunification problems.

**Proposition 4.1.** *The rule ElimAnti is sound and preserving modulo  $\mathcal{E}$ .*

The normal forms *w.r.t.* ElimAnti of anti-pattern matching problems are specific equational problems. Although equational problems are undecidable in general [22], even in case of  $\mathcal{A}$  or  $\mathcal{AU}$  theories, we will see that the specific equational problems issued from anti-pattern matching are decidable for  $\mathcal{A}$  or  $\mathcal{AU}$  theories.

Summarizing, if we know how to solve equational problems modulo  $\mathcal{E}$ , then any anti-pattern matching problem modulo  $\mathcal{E}$  can be translated into equivalent equational problems using ElimAnti and further solved. These statements are formalized by the following Proposition:

**Proposition 4.2.** *An anti-pattern matching problem can always be translated into an equivalent equational problem in a finite number of steps.*

*Proof.* We showed in the proof of Proposition 4.1 that ElimAnti preserves the solutions if applied on a matching problem. Each of its applications transforms one equation in two equivalent equations (that preserve solutions). Each new equation contains less occurrences of  $\neg$ , therefore, for a finite number  $n$  of  $\neg$  symbols, ElimAnti terminates and it is easy to show that the normal forms contain at most  $2^n$  equations and disequations.  $\square$

Solving equational problems resulted from normalization with ElimAnti can be performed with techniques like disunification for instance in the case of syntactic theory. These techniques were designed to cover more general problems. In our case, a more efficient and tailored approach can be developed. Given a finitary  $\mathcal{E}$ -match algorithm, a first solution would be to normalize each match equation separately, then to combine the results using replacements and some cleaning rules (as ForAll, NotOr, NotTrue, NotFalse from Figure 2). This approach can be used to effectively solve  $\mathcal{A}$ ,  $\mathcal{AU}$ , and  $\mathcal{AC}$  anti-pattern matching problems. We further detail the  $\mathcal{AU}$  case.

## 4.2 A specific case: matching $\mathcal{AU}$ anti-patterns

To compute the set of solutions for an  $\mathcal{AU}$  anti-pattern matching equation we develop now a specific approach.

**Definition 4.5.**  *$\mathcal{AU}$ -AntiMatching: Given an  $\mathcal{AU}$  anti-pattern matching problem  $q \prec_{\mathcal{AU}} t$ , apply the rules from Figure 2, giving a higher priority to ElimAnti.*

Note that instead of giving a higher priority to ElimAnti the algorithm can be decomposed in two steps: first normalize with ElimAnti to eliminate all  $\neg$  symbols, then apply all the other rules.

We further prove that the algorithm is correct. Moreover, the normal forms of its application on an  $\mathcal{AU}$  anti-pattern matching equation do not contain any  $\neg$  or *not* symbols. Actually they are the same as the ones exposed in Theorem 3.1.

ElimAnti	$q[\neg q']_\omega \ll_{\mathcal{AU}} t \mapsto \exists z q[z]_\omega \ll_{\mathcal{AU}} t \wedge \forall x \in \mathcal{FVar}(q') \text{ not}(q[q']_\omega \ll_{\mathcal{AU}} t)$ if $\forall \omega' < \omega, q(\omega') \neq \neg$ and $z$ a fresh variable	
ForAll	$\forall \bar{y} \text{ not}(D) \mapsto \text{not}(\exists \bar{y} D)$	
NotOr	$\text{not}(D_1 \vee D_2) \mapsto \text{not}(D_1) \wedge \text{not}(D_2)$	
NotTrue	$\text{not}(\top) \mapsto \perp$	
NotFalse	$\text{not}(\perp) \mapsto \top$	
<i><math>\mathcal{AU}</math>-Matching rules:</i>		
Mutate	$f(p_1, p_2) \ll_{\mathcal{AU}} f(t_1, t_2) \mapsto (p_1 \ll_{\mathcal{AU}} t_1 \wedge p_2 \ll_{\mathcal{AU}} t_2) \vee$ $\exists x(p_2 \ll_{\mathcal{AU}} f(x, t_2) \wedge f(p_1, x) \ll_{\mathcal{AU}} t_1) \vee$ $\exists x(p_1 \ll_{\mathcal{AU}} f(t_1, x) \wedge f(x, p_2) \ll_{\mathcal{AU}} t_2)$	
SymbolClash <sub>1</sub> <sup>+</sup>	$f(p_1, p_2) \ll_{\mathcal{AU}} a \mapsto (p_1 \ll_{\mathcal{AU}} e_f \wedge p_2 \ll_{\mathcal{AU}} a) \vee (p_1 \ll_{\mathcal{AU}} a \wedge p_2 \ll_{\mathcal{AU}} e_f)$	
SymbolClash <sub>2</sub> <sup>+</sup>	$a \ll_{\mathcal{AU}} f(p_1, p_2) \mapsto (e_f \ll_{\mathcal{AU}} p_1 \wedge a \ll_{\mathcal{AU}} p_2) \vee (a \ll_{\mathcal{AU}} p_1 \wedge e_f \ll_{\mathcal{AU}} p_2)$	
ConstantClash	$a \ll_{\mathcal{AU}} b \mapsto \perp$ if $a \neq b$	
Replacement	$z \ll_{\mathcal{AU}} t \wedge S \mapsto z \ll_{\mathcal{AU}} t \wedge \{z \mapsto t\}S$ if $z \in \mathcal{FVar}(S)$	
<i>Utility Rules:</i>		
Delete	$p \ll_{\mathcal{AU}} p \mapsto \top$	PropagClash <sub>1</sub> $S \wedge \perp \mapsto \perp$
Exists <sub>1</sub>	$\exists z(D[z \ll_{\mathcal{AU}} t]) \mapsto D[\top]$ if $z \notin \mathcal{Var}(D[\top])$	PropagClash <sub>2</sub> $S \vee \perp \mapsto S$
Exists <sub>2</sub>	$\exists z(S_1 \vee S_2) \mapsto \exists z(S_1) \vee \exists z(S_2)$	PropagSuccess <sub>1</sub> $S \wedge \top \mapsto S$
DistribAnd	$S_1 \wedge (S_2 \vee S_3) \mapsto (S_1 \wedge S_2) \vee (S_1 \wedge S_3)$	PropagSuccess <sub>2</sub> $S \vee \top \mapsto \top$

Fig. 2.  $\mathcal{AU}$ -AntiMatching

**Proposition 4.3.** *The application of  $\mathcal{AU}$ -AntiMatching is sound and preserving.*

*Proof.* For ElimAnti these properties were showed in the proof of Proposition 4.1. Similarly, Proposition 3.3 states the sound and preserving properties for the rules of  $\mathcal{AU}$ -Matching. The rest of the rules are trivial.  $\square$

**Theorem 4.1.** *The normal forms of  $\mathcal{AU}$ -AntiMatching are  $\mathcal{AU}$ -matching problems in solved form.*

$\mathcal{AU}$ -AntiMatching is a general algorithm, that solves any anti-pattern matching problem. Note that it can produce  $2^n$  matching equations, where  $n$  is the number of  $\neg$  symbols in the initial problem. For instance, applying ElimAnti on  $f(a, \neg b) \ll_{\mathcal{AU}} f(a, a)$  gives  $\exists z f(a, z) \ll_{\mathcal{AU}} f(a, a) \wedge \text{not}(f(a, b) \ll_{\mathcal{AU}} f(a, a))$ . Note that all equations have the same right-hand sides  $f(a, a)$ , and *almost* the same left-hand sides  $f(a, -)$ . Therefore, when solving the second equation for instance, we perform some matches that were already done when solving the first one. This approach is clearly not optimal, and in the following we propose a more efficient one.

### 4.3 A more efficient algorithm for $\mathcal{AU}$ anti-pattern matching

In this section we consider a subclass of anti-patterns, called *PureFVars*, and we present a more efficient algorithm that has the same complexity as  $\mathcal{AU}$ -Matching. In particular, it does no longer produce the  $2^n$  equations introduced by  $\mathcal{AU}$ -AntiMatching.

**Definition 4.6.** Given  $\mathcal{F}, \mathcal{X}$  we define a subclass of anti-patterns:

$$Pure\mathcal{FVars} = \left\{ q \in \mathcal{AT}(\mathcal{F}, \mathcal{X}) \mid \begin{array}{l} q = C[f(t_1, \dots, t_i, \dots, t_j, \dots, t_n)], \\ \forall i \neq j, \mathcal{FVar}(t_i) \cap \mathcal{NFVar}(t_j) = \emptyset \end{array} \right\}$$

The anti-patterns in  $Pure\mathcal{FVars}$  are special cases of non-linearity respecting that at any position, we don't find a term that has a free variable in one of its children, and the same variable under a  $\neg$  in another child. For instance,  $f(x, x) \in Pure\mathcal{FVars}$ ,  $f(\neg x, \neg x) \in Pure\mathcal{FVars}$ , but  $f(x, \neg x) \notin Pure\mathcal{FVars}$ .

**Definition 4.7.**  $\mathcal{AU}$ -AntiMatchingEfficient: The algorithm corresponds to  $\mathcal{AU}$ -AntiMatching, where the rule `ElimAnti` is replaced with the following one, and which has no longer any priority:

$$\text{ElimAnti}' \quad \neg q \ll_{\mathcal{AU}} t \mapsto \forall x \in \mathcal{FVar}(q) \text{ not}(q \ll_{\mathcal{AU}} t)$$

Note that our algorithms are finitary and based on decomposition. Therefore, when considering syntactic or regular theories the composition results for matching algorithms are still valid. Note also that  $Pure\mathcal{FVars}$  is trivially stable *w.r.t.* to this algorithm and that now the rules apply on problems that potentially contain  $\neg$  symbols. For instance, we may apply the rule `Mutate` on  $f(a, \neg b) \ll_{\mathcal{AU}} f(a, a)$ . The algorithm is still terminating, with the same arguments as in the proof of Proposition 3.1, but the proof of Proposition 3.3 is no longer valid in this new case. The correctness of the algorithm has to be established again:

**Proposition 4.4.** Given  $q \ll_{\mathcal{AU}} t$ , with  $q \in Pure\mathcal{FVars}$ , the application of  $\mathcal{AU}$ -AntiMatchingEfficient is sound and preserving.

This approach is much more efficient, as no duplications are being made. Let us see on a simple example:  $f(x, \neg a) \ll_{\mathcal{AU}} f(a, b) \mapsto_{\text{Mutate}} (x \ll_{\mathcal{AU}} a \wedge \neg a \ll_{\mathcal{AU}} b) \vee D_1 \vee D_2 \mapsto_{\text{ElimAnti}' } (x \ll_{\mathcal{AU}} a \wedge \text{not}(a \ll_{\mathcal{AU}} b)) \vee D_1 \vee D_2 \mapsto_{\text{ConstantClash}} (x \ll_{\mathcal{AU}} a \wedge \text{not}(\perp)) \vee D_1 \vee D_2 \mapsto_{\text{NotFalse, PropagSuccess}_2} x \ll_{\mathcal{AU}} a \vee D_1 \vee D_2$ . We continue in a similar way for  $D_1, D_2$  and we finally obtain the solution  $\{x \mapsto a\}$ .

In practice, when implementing an anti-pattern matching algorithm, one can imagine the following approach: a traversal of the term is done, and if the special non-linear case is detected (*i.e.*  $\notin Pure\mathcal{FVars}$ ), then  $\mathcal{AU}$ -AntiMatching is applied; otherwise we apply  $\mathcal{AU}$ -AntiMatchingEfficient. This is the method used in the TOM compiler for instance.

In this section we have given a general algorithm for solving  $\mathcal{AU}$  anti-pattern matching problems, and a more efficient one for a subclass which encompasses most of the practical cases. We also conjecture that modifying the universal quantification of `ElimAnti'` to only quantify variables that respect the condition  $\mathcal{FVar}(q_1) \cap \mathcal{NFVar}(q_2) = \emptyset$  of  $Pure\mathcal{FVars}$ , would still lead to a sound and complete algorithm. For instance, when applying `ElimAnti'` to  $f(x, \neg x)$ , the variable  $x$  would not be quantified. This algorithm has been experimented and tested without showing any counter example. Proving this conjecture is part of our future work.

## 5 Anti-matching modulo in Tom

Anti-patterns are successfully integrated in the TOM language for syntactic and  $\mathcal{AU}$  matching. In this section we show how they can be used and illustrate the expressiveness they add to the pattern matching capabilities of this language. It is worth mentioning that for all the theories considered, the size of the generated code is *linear* in the size of the patterns.

In order to support anti-patterns, we enriched the syntax of the TOM patterns to allow the use of operator ‘!’ (representing ‘ $\neg$ ’). For syntactic matching, here is an example of a *match* in TOM:

```
%match(s) {
  f(a(),g(b())) -> { /* executed when f(a,g(b))<<s */ }
  f(!a(),g(b())) -> { /* when f(x,g(b))<<s with x!=a */ }
  !f(x,!g(x)) -> { /* when not f(x,y)<<s or ... */ }
  !f(x,g(y)) -> { /* action 4 */ }
}
```

Similarly to `switch/case`, an action part is executed when its corresponding pattern matches the subject `s`. Note that non-linear patterns are allowed. When combined with lists, anti-patterns are even more useful:

```
%match(s) {
  l(*,a(),_*) -> { /* executed when s contains a */ }
  l(*,!a(),_*) -> { /* s has one elem. diff. from a*/ }
  !l(*,a(),_*) -> { /* s does not contain a */ }
  !l(*,!a(),_*) -> { /* s contains only a */ }
  l(*,x,*,x,*) -> { /* s has at least 2 equal elem.*/ }
  !l(*,x,*,x,*) -> { /* s has only distinct elem. */ }
  l(*,x,*,!,x,*) -> { /* s has at least 2 diff elem. */ }
  !l(*,x,*,!,x,*) -> { /* when s has only equal elem. */ }
}
```

In the above patterns `l` is  $\mathcal{AU}$ , a `*` stands for any sublist, `a()` is a constant and `x` is a variable that cannot be instantiated by the empty list. Note that we mainly used the constant `a()`, but any other pattern or anti-pattern could have been used instead, like in: `l(*,f(!a(),g(b())),_*)`, or `!l(*,f(!a(),g(b())),_*)`. There is no restriction.

The following example prints all the elements that do not appear twice or more in a list `s`:

```
%match(s,s) {
  l(*,x,*) , !l(*,x,*,x,*) -> { print(x); }
}
```

For instance, if `s` is instantiated with the list of integers `(1,2,1,3,2,1,5)`, the above code would output: `3` and `5`. Note that the `,` between the two patterns, like in functional programming languages, has the same meaning as any `,` inside a pattern. The idea is that the first pattern selects an element from the list, and the second one verifies that it doesn't appear twice.

Without using anti-patterns, one would be forced to verify additional conditions in the action part, which would make the code more complicated and difficult to maintain (see [15], Section 6). Besides, they may improve efficiency, by verifying some conditions earlier in the matching process.

## 6 Related work

After generalizing the notion of anti-patterns to an arbitrary equational theory, we focused on the  $\mathcal{AU}$  theory. As we deal with terms (seen as trees), the pattern matching on XML documents is probably the closest to this work – as XML documents are trees built over associative-commutative symbols. We compare in this section the capabilities to express negative conditions of the main query languages with our approach based on anti-patterns.

TQL [6] is a query language for semistructured data based on the ambient logic that can be used to query XML files. It is a very expressive language and it can be used to capture most of the examples we provided along the paper. Moreover, TQL supports unlimited negation. The data model of TQL is unordered, it relies on  $\mathcal{AC}$  operators and unary ones. Therefore, syntactic patterns are not supported in their full generality. For instance, it is not possible to express a pattern such as  $\neg f(a, \neg b)$ . More generally, syntactic anti-patterns and associative operators cannot be combined. In [6], the authors state that the extension of TQL with ordering is an important open issue. Compared to TQL, TOM is a mature implementation that can be easily integrated in a JAVA programming environment. It also offers good performance when dealing with large documents.

XDO2 [23] is another query language for XML. It expresses negation with the use of a *not-predicate*, thus being able to support nested negations and negation of sub-trees. For instance, the following query retrieves the companies that don't have employees who have the sex  $M$  and age  $40$ :

```
/db/company:$c <= /root/company : $c/not(employee/[sex:"M",age:40])
```

In [23] the authors present the main features of the language, but they do not provide the semantics for negations in the general case. The examples that they offer in [23] are simple cases of negations, easy to express both in TQL and in the presented anti-pattern framework. Note also that non-linearity (which is a difficult and important part) was not studied in [23].

XQuery provides a function *not()* for supporting negations. It can only be applied on a boolean argument, and returns the inverse value of its argument. The language also provides constructs like *some* and *every* which can be used to obtain the semantics of some anti-patterns. But this gives quite complicated queries that could be a lot simpler and compact by using anti-patterns.

ASF+SDF has a basic form of negative matching condition, denoted  $p! := \neg t$ , but nested negations are not supported.

## 7 Conclusion

We have generalized the notion of anti-pattern matching to anti-pattern matching modulo an arbitrary regular theory  $\mathcal{E}$ . Because of their usefulness for rule-based programming, we chose to exemplify the anti-patterns for the  $\mathcal{A}$  and  $\mathcal{AU}$  theories.

What is worth noting is that the algorithms we presented are not necessarily specific to  $\mathcal{AU}$ , and that they can be used for other theories as well (like the empty one,  $\mathcal{AC}$ , etc), just by adapting the  $\mathcal{AU}$  rules to the considered theory. This is quite interesting even for the syntactical case, as the disunification-based algorithm presented in [15] is not appropriate for an efficient implementation.

Although some of the results may at first glance seem straightforward, subtle details are not so easy to establish. The main difficulties come from matching non-linear anti-patterns, which cannot be performed using classical decomposition rules, as the semantics are not preserved.

The work in this paper opens a number of challenging directions like proving the correctness of the third algorithm presented as a conjecture. We also plan to study some theoretical properties such as the confluence, termination, and complete definition of systems that include anti-patterns. Another interesting direction is the study of unification problems in the presence of anti-patterns.

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## A Proof of Proposition 3.1

**Proposition 3.1.** *Given a matching equation  $p \ll_{\mathcal{A}} t$  with  $p \in \mathcal{T}(\mathcal{F}, \mathcal{X})$ ,  $t \in \mathcal{T}(\mathcal{F})$ , the application of  $\mathcal{A}$ -Matching always terminates.*

*Proof.* As we deal with a matching problem (where the right-hand side is a ground term), we are interested in a derivation of this problem. For this, the size measure we further define is relative to the size of the right-hand side of the initial problem – always bigger or equal to the left-hand side in order for the match to have a solution.

Let  $D_0$  be the initial problem, *i.e.*  $D_0 = p \ll_{\mathcal{A}} t$ . Further on,  $D_0 \#_{\mathcal{A}\text{-Matching}} D_1 \#_{\mathcal{A}\text{-Matching}} \dots \#_{\mathcal{A}\text{-Matching}} D_n$ . For all  $i \in [1 \dots n]$ , the size



of  $D_i$ , denoted by  $\|D_i\|$ , is the multiset of its components, computed in the following way:

- $\|D_j \wedge D_k\| = \|D_j \vee D_k\| = \|D_i\| \cup \|D_j\|$ ,
- $\|\exists z(D_j)\| = \|D_j\|$ ,
- $\|\perp\| = \|\top\| = \{0\}$ ,
- $\|p' \ll_{\mathcal{A}} t'\| = \{\|t'\|\}$ ,
- $\|f(t_1, t_2)\| = 1 + \|t_1\| + \|t_2\|$ ,
- $\|a\| = 1$ , for  $a$  a constant,
- $\|x\| = \|t\|$ , if  $x \in \text{Var}(p)$ , *i.e.* a free variable of the initial problem  $D_0$ ,
- $\|x\| = \|t_j\| - 1$ , if  $x \notin \text{Var}(D_i)$  and  $D_{i+1} = C[\exists x(C'[p_j \ll_{\mathcal{A}} t_j])]$  with  $x \in \text{Var}(p_j)$  — here  $C$  denotes the context. Therefore, each time a new existential variable is introduced, its size is computed and it remains unchanged afterwards.

Note that when an existential variable is introduced in a left-hand side of an equation, its size is fixed to the size of the right-hand side minus 1. As further applications of the algorithm never increase the right-hand side, when solved, this variable's size can't exceed its fixed size. Moreover, it is instantiated with its size minus 1, as we can observe from the equations of the right-hand side of **Mutate**:  $x$  can only be instantiated in the second equation from  $f(p_1, x) \ll_{\mathcal{A}} t_1$ . But  $\|f(p_1, x)\| \leq \|t_1\| \Rightarrow 1 + \|p_1\| + \|x\| \leq \|t_1\| \Rightarrow \|x\| \leq \|t_1\| - 1 - \|p_1\|$  which finally results in  $\|x\| < \|t_1\| - 1$ . For the third equation, the reasoning is the same.

The number of variables' occurrences in  $D$  is the sum of the occurrences in each term, and is denoted by  $\#\text{Var}(D)$ , *i.e.*  $\#\text{Var}(D) = \sum \#\text{Var}(t)$ , for all  $t \in D$ . The variables' occurrences in a term are computed as  $\#\text{Var}(t) = \#\{\omega \mid t|_{\omega} \in \mathcal{X}\}$ .

Termination is easy to show for all the rules, except **Mutate** and **Replacement**. Therefore, we focus on these two rules and we consider a lexicographical order  $\phi = (\phi_1, \phi_2)$ , where  $\phi_1 = \|D\|$ , and  $\phi_2 = \#\text{Var}(D)$ , which is decreasing for the application of each of the two rules:

- **Mutate**:  $\|f(p_1, p_2) \ll_{\mathcal{A}} f(t_1, t_2)\| = \{\|f(t_1, t_2)\|\} = \{1 + \|t_1\| + \|t_2\|\}$ . The size of each equation from the right-hand side is strictly smaller:
  - $\|p_1 \ll_{\mathcal{A}} t_1\| = \|t_1\|$
  - $\|p_2 \ll_{\mathcal{A}} t_2\| = \|t_2\|$
  - $\|p_2 \ll_{\mathcal{A}} f(x, t_2)\| = \{\|f(x, t_2)\|\} < \{\|f(t_1, t_2)\|\}$  as  $\|x\| = \|t_1\| - 1$ .
  - $\|f(p_1, x) \ll_{\mathcal{A}} t_1\| = \|t_1\|$
  - $\|p_1 \ll_{\mathcal{A}} f(t_1, x)\| = \{\|f(t_1, x)\|\} < \{\|f(t_1, t_2)\|\}$  as  $\|x\| = \|t_2\| - 1$ .
  - $\|f(x, p_2) \ll_{\mathcal{A}} t_2\| = \|t_2\|$

Therefore for the right-hand side of the rule  $\phi_1 = \{\{\|t_1\|\}, \{\|t_2\|\}, \{\|t_1\| + \|t_2\|\}, \{\|t_1\|\}, \{\|t_1\| + \|t_2\|\}, \{\|t_2\|\}\}$  strictly smaller than the size of the left-hand side  $\{\{1 + \|t_1\| + \|t_2\|\}\}$ . This implies that  $\phi_1$  is decreasing, and although  $\phi_2$  increases (because we add new variables),  $\phi$  is lexicographically decreasing.

- **Replacement:** we deal with two types of variables – the free and the quantified ones:
    - when replacing a free variable, the size remains constant, as all the variables are in the left-hand sides. Therefore  $\phi_1$  is constant, but  $\phi_2$  is strictly decreasing.
    - when introduced (by the rule **Mutate**), a quantified variable appears twice: once on the left-hand side of an equation, and once on the right-hand side. Therefore, this occurrence on the left-hand side, when instantiated, will be used to replace the one in the right-hand side. But, as we noticed before, they can only be instantiated with a term smaller than their size. Consequently, when replaced in an equation  $E$ , the size of  $E$  decreases. Therefore  $\phi_1$  is strictly decreasing.
- Thus, in both cases  $\phi$  is decreasing.  $\square$

## B Proof of Theorem 3.1

**Theorem 3.1.** *Given a matching equation  $p \ll_{\mathcal{A}} t$ , with  $p \in \mathcal{T}(\mathcal{F}, \mathcal{X})$  and  $t \in \mathcal{T}(\mathcal{F})$ , the normal form w.r.t.  $\mathcal{A}$ -Matching exists and it is unique. It can only be of the following types:*

1.  $\top$ , then  $p$  and  $t$  are identical modulo  $\mathcal{A}$ , i.e.  $p =_{\mathcal{A}} t$ ;
2.  $\perp$ , then there is no match from  $p$  to  $t$ ;
3. a disjunction of conjunctions  $\bigvee_{j \in J} (\bigwedge_{i \in I} x_{i_j} \ll_{\mathcal{A}} t_{i_j})$  with  $I, J \neq \emptyset$ , then the substitutions  $\sigma_j = \{x_{i_j} \mapsto t_{i_j}\}_{i \in I, j \in J}$  are all the matches from  $p$  to  $t$ ;

*Proof.* From Proposition 3.1 a normal form always exists. Moreover, from Proposition 3.2 we can infer that it is unique, as after the application of  $\mathcal{A}$ -Matching we have the same solutions as the initial problem. Therefore, we have to prove that (i) all the quantifiers are eliminated and (ii) all match-equation's left-hand sides are variables of the initial equation. We only have existential quantifiers, introduced by **Mutate**, which are distributed to each conjunction by **Exists<sub>2</sub>** and later eliminated by the rule **Exists<sub>1</sub>**. The validity of the condition of this latter rule is ensured by the rule **Replacement**, which leaves only one occurrence of each variable in a conjunction. On the other hand, we never eliminate free variables in a conjunction (only some duplicates), which justifies (ii). Finally, all normal forms are necessarily of the form (1), (2) or (3), otherwise a rule could be further applied.  $\square$

## C Proof of Proposition 3.3

The proof of Proposition 3.3 uses the following lemma:

**Lemma C.1.** *Let  $t_1$  and  $t_2$  be two ground terms. Matching them modulo  $\mathcal{AU}$  is equivalent to match modulo  $\mathcal{A}$  their  $\mathcal{U}$ -normal forms (denoted  $t_{1 \downarrow \mathcal{U}}$  and  $t_{2 \downarrow \mathcal{U}}$ ):*

$$t_1 \ll_{\mathcal{AU}} t_2 \Leftrightarrow t_{1 \downarrow \mathcal{U}} \ll_{\mathcal{A}} t_{2 \downarrow \mathcal{U}}$$

*Proof.* Direct application of [11, Theorem 3.3], since the unit rules are linear and terminating modulo  $\mathcal{A}$ , and associativity is regular.  $\square$

**Proposition 3.3.** *The rules of  $\mathcal{AU}$ -Matching are sound and preserving modulo  $\mathcal{AU}$ .*

*Proof.* Thanks to Proposition 3.2, we know that the rules are sound and preserving modulo  $\mathcal{A}$ . In order to be also valid modulo  $\mathcal{AU}$ , they have to remain valid in the presence of the equations for neutral elements, as defined in Section 2.

Let us first see the preserving property of the rules:

- ConstantClash, Replacement, Delete, Exists<sub>1</sub>, Exists<sub>2</sub>, DistribAnd, PropagSuccess<sub>1</sub>, PropagClash<sub>1</sub>, PropagSuccess<sub>2</sub>, PropagClash<sub>2</sub>: these rules do not depend on the theory we consider.
- Mutate: we need to prove that for  $\sigma \in \text{Sol}(f(p_1, p_2) =_{\mathcal{AU}} f(t_1, t_2))$ ,  $\exists \rho$  such that at least one of the following is true:
  - $\sigma\rho(p_1) =_{\mathcal{AU}} \rho(t_1) \wedge \sigma\rho(p_2) =_{\mathcal{AU}} \rho(t_2)$
  - $\sigma\rho(p_2) =_{\mathcal{AU}} \rho(f(x, t_2)) \wedge \sigma\rho(f(p_1, x)) =_{\mathcal{AU}} \rho(t_1)$
  - $\sigma\rho(p_1) =_{\mathcal{AU}} \rho(f(t_1, x)) \wedge \sigma\rho(f(x, p_2)) =_{\mathcal{AU}} \rho(t_2)$

which are equivalent, by Lemma C.1, to:

1.  $\sigma\rho(p_1)_{\downarrow \mathcal{U}} =_{\mathcal{A}} \rho(t_1)_{\downarrow \mathcal{U}} \wedge \sigma\rho(p_2)_{\downarrow \mathcal{U}} =_{\mathcal{A}} \rho(t_2)_{\downarrow \mathcal{U}}$
2.  $\sigma\rho(p_2)_{\downarrow \mathcal{U}} =_{\mathcal{A}} \rho(f(x, t_2))_{\downarrow \mathcal{U}} \wedge \sigma\rho(f(p_1, x))_{\downarrow \mathcal{U}} =_{\mathcal{A}} \rho(t_1)_{\downarrow \mathcal{U}}$
3.  $\sigma\rho(p_1)_{\downarrow \mathcal{U}} =_{\mathcal{A}} \rho(f(t_1, x))_{\downarrow \mathcal{U}} \wedge \sigma\rho(f(x, p_2))_{\downarrow \mathcal{U}} =_{\mathcal{A}} \rho(t_2)_{\downarrow \mathcal{U}}$

But  $\sigma \in \text{Sol}(f(p_1, p_2) =_{\mathcal{AU}} f(t_1, t_2)) \Rightarrow f(\sigma\rho(p_1), \sigma\rho(p_2)) =_{\mathcal{AU}} f(\rho(t_1), \rho(t_2))$  for a chosen  $\rho$  which is equivalent to  $f(\sigma\rho(p_1), \sigma\rho(p_2))_{\downarrow \mathcal{U}} =_{\mathcal{A}} f(\rho(t_1), \rho(t_2))_{\downarrow \mathcal{U}}$ . We have the following possible cases:

1. neither  $f(\sigma\rho(p_1), \sigma\rho(p_2))$  nor  $f(\rho(t_1), \rho(t_2))$  can be reduced by  $\mathcal{U}$ . This means that  $f(\sigma\rho(p_1), \sigma\rho(p_2)) =_{\mathcal{AU}} f(\rho(t_1), \rho(t_2)) \Leftrightarrow f(\sigma\rho(p_1), \sigma\rho(p_2)) =_{\mathcal{A}} f(\rho(t_1), \rho(t_2))$ , which implies (by the rule Mutate that was proved to be  $\mathcal{A}$ -preserving) the disjunction of the three cases above.
  2. only  $f(\sigma\rho(p_1), \sigma\rho(p_2))$  can be reduced by  $\mathcal{U}$ :
    - (a)  $\sigma\rho(p_1)_{\downarrow \mathcal{U}} \neq e_f, \sigma\rho(p_2)_{\downarrow \mathcal{U}} \neq e_f$ . This gives  $f(\sigma\rho(p_1)_{\downarrow \mathcal{U}}, \sigma\rho(p_2)_{\downarrow \mathcal{U}}) =_{\mathcal{A}} f(\rho(t_1), \rho(t_2))$  which again implies the three cases above.
    - (b)  $\sigma\rho(p_1)_{\downarrow \mathcal{U}} = e_f$ . This results in  $\sigma\rho(p_2)_{\downarrow \mathcal{U}} =_{\mathcal{A}} f(\rho(t_1), \rho(t_2))$  which is equivalent with the second case for  $\rho(x) = \rho(t_1)$ .
    - (c)  $\sigma\rho(p_2)_{\downarrow \mathcal{U}} = e_f$ . Implies the second case with  $\rho(x) = \rho(t_2)$ .
  3. only  $f(\rho(t_1), \rho(t_2))$  can be reduced. As above, we consider all the three possible cases reasoning exactly in the same fashion.
  4. both  $f(\sigma\rho(p_1), \sigma\rho(p_2))$  and  $f(\rho(t_1), \rho(t_2))$  are reducible. This case is just the combination of all the possibilities we have enounced above, therefore nine cases, which are solved similarly.
- SymbolClash<sub>1</sub><sup>+</sup>:  $\sigma \in \text{Sol}(f(p_1, p_2) =_{\mathcal{AU}} g(\bar{t})) \Rightarrow f(\sigma(p_1), \sigma(p_2))_{\downarrow \mathcal{U}} =_{\mathcal{A}} a$ 
    - a. When both  $\sigma(p_1)_{\downarrow \mathcal{U}}$  and  $\sigma(p_2)_{\downarrow \mathcal{U}}$  are different from  $e_f$ , the equation  $f(\sigma(p_1)_{\downarrow \mathcal{U}}, \sigma(p_2)_{\downarrow \mathcal{U}}) =_{\mathcal{A}} a$  has no solution as SymbolClash can be applied. If at least one of them is equal to  $e_f$ , we have the exact correspondence with the right-hand side of the rule:  $\sigma(p_1)_{\downarrow \mathcal{U}} =_{\mathcal{A}} e_f \wedge \sigma(p_2)_{\downarrow \mathcal{U}} =_{\mathcal{A}} a \vee \sigma(p_1)_{\downarrow \mathcal{U}} =_{\mathcal{A}} a \wedge \sigma(p_2)_{\downarrow \mathcal{U}} =_{\mathcal{A}} e_f$ .

–  $\text{Symbol Clash}_2^+$ : The same reasoning as above.

The soundness justification follows the same pattern. For example, for the rule  $\text{Mutate}$ , which is the most interesting one, we have to prove that there exists  $\rho$ , such that that given  $\sigma$  which validates at least one of the disjunctions, we obtain the left-hand side of the rule. As above, first case is when only  $\sigma\rho(p_1)$  and  $\sigma\rho(p_2)$  can be reduced by  $\mathcal{U}$ , and  $\sigma\rho(p_1)_{\downarrow\mathcal{U}} \neq e_f$  and  $\sigma\rho(p_2)_{\downarrow\mathcal{U}} \neq e_f$ . The question if  $\sigma\rho(p_1)_{\downarrow\mathcal{U}} =_{\mathcal{A}} \rho(t_1) \wedge \sigma\rho(p_2)_{\downarrow\mathcal{U}} =_{\mathcal{A}} \rho(t_2)$  implies  $f(\sigma(p_1)_{\downarrow\mathcal{U}}, \sigma\rho(p_2)_{\downarrow\mathcal{U}}) =_{\mathcal{A}} f(\rho(t_1), \rho(t_2))$  is obviously true. The rest of the cases are similar.  $\square$

## D Proof of Proposition 4.1

**Proposition 4.1.** *The rule  $\text{ElimAnti}$  is sound and preserving modulo  $\mathcal{E}$ .*

*Proof.* We consider a position  $\omega$  such that  $q[\neg q']_{\omega}$  and  $\forall \omega' < \omega, q(\omega') \neq \neg$ . Considering as usual that  $\text{Sol}(A \wedge B) = \text{Sol}(A) \cap \text{Sol}(B)$  we have the following result for the right-hand side of the rule:

$$\begin{aligned} & \text{Sol}(\exists z q[z]_{\omega} \ll_{\mathcal{E}} t \wedge \forall x \in \mathcal{FVar}(q') \text{ not}(q[q']_{\omega} \ll_{\mathcal{E}} t)) \\ &= \text{Sol}(\exists z q[z]_{\omega} \ll_{\mathcal{E}} t) \cap \text{Sol}(\forall x \in \mathcal{FVar}(q') \text{ not}(q[q']_{\omega} \ll_{\mathcal{E}} t)) \end{aligned}$$

From Definition 4.4,  $\text{Sol}(\exists z q[z]_{\omega} \ll_{\mathcal{E}} t)$  is equal to:

$$\{\sigma \mid \text{Dom}(\sigma) = \mathcal{FVar}(q[z]) \setminus \{z\} \text{ and } \exists \rho \text{ with } \text{Dom}(\rho) = \{z\}, \\ t \in \llbracket \rho\sigma(q[z]_{\omega}) \rrbracket_{g_{\mathcal{E}}}\} \quad (1)$$

Also from Definition 4.4,  $\text{Sol}(\forall x \in \mathcal{FVar}(q') \text{ not}(q[q']_{\omega} \ll_{\mathcal{E}} t))$  is equal to:

$$\{\sigma \mid t \notin \llbracket \sigma(q[q']_{\omega}) \rrbracket_{g_{\mathcal{E}}} \text{ with } \text{Dom}(\sigma) = \mathcal{FVar}(q[q']) \\ \setminus \mathcal{FVar}(q')\} \quad (2)$$

For the left part of the rule  $\text{ElimAnti}$ , by Definition 4.3, we have:

$$\begin{aligned} & \text{Sol}(q[\neg q']_{\omega} \ll_{\mathcal{E}} t) \\ &= \{\sigma \mid t \in \llbracket \sigma(q[\neg q']_{\omega}) \rrbracket_{g_{\mathcal{E}}}, \text{ with } \text{Dom}(\sigma) = \mathcal{FVar}(q[\neg q'])\} \\ &= \{\sigma \mid t \in (\llbracket \sigma(q[z]_{\omega}) \rrbracket_{g_{\mathcal{E}}} \setminus \llbracket \sigma(q[q']_{\omega}) \rrbracket_{g_{\mathcal{E}}}), \text{ with } \dots\}, \\ & \quad \text{since } \forall \omega' < \omega, q(\omega') \neq \neg \\ &= \{\sigma \mid t \in \llbracket \sigma(q[z]_{\omega}) \rrbracket_{g_{\mathcal{E}}} \text{ and } t \notin \llbracket \sigma(q[q']_{\omega}) \rrbracket_{g_{\mathcal{E}}}, \\ & \quad \text{with } \text{Dom}(\sigma) = \mathcal{FVar}(q[\neg q'])\} \\ &= \{\sigma \mid t \in \llbracket \sigma(q[z]_{\omega}) \rrbracket_{g_{\mathcal{E}}}, \text{ with } \dots\} \\ & \quad \cap \{\sigma \mid t \notin \llbracket \sigma(q[q']_{\omega}) \rrbracket_{g_{\mathcal{E}}}, \text{ with } \dots\} \end{aligned} \quad (3)$$

Now it remains to check the equivalence of (3) with the intersection of (1) and (2). First of all,  $\mathcal{FVar}(q[z]) \setminus \{z\} = \mathcal{FVar}(q[q']) \setminus \mathcal{FVar}(q') = \mathcal{FVar}(q[\neg q'])$  which means that we have the same domain for  $\sigma$  in (3), (1), and (2). Therefore, we have to prove:

$$\begin{aligned} & \{\sigma \mid \exists \rho \text{ with } \text{Dom}(\rho) = \{z\} \text{ and } t \in \llbracket \rho\sigma(q[z]_{\omega}) \rrbracket_{g_{\mathcal{E}}}\} \\ &= \{\sigma \mid t \in \llbracket \sigma(q[z]_{\omega}) \rrbracket_{g_{\mathcal{E}}}\} \end{aligned} \quad (4)$$

But  $\sigma$  does not instantiate  $z$ , and this means that the ground semantics will give to  $z$  all the possible values for the right part of (4). At the same time, having  $\rho$  existentially quantified allows  $z$  to be instantiated with any value such that  $t \in \llbracket \rho\sigma(q[z]_\omega) \rrbracket_{g\varepsilon}$  is valid, and therefore (4) is true. As we considered an arbitrary  $\top$ , we can conclude that the rule is sound and preserving, wherever it is applied on a term.  $\square$

## E Proof of Theorem 4.1

**Theorem 4.1.** *The normal forms of  $\mathcal{AU}$ -AntiMatching are  $\mathcal{AU}$ -matching problems in solved form.*

*Proof.* The normal forms clearly do not contain any  $\top$  symbols, as we normalize with `ElimAnti`. Universal quantifications are also eliminated by the rule `ForAll` followed by `Exists1` and `Exists2`. Let us now prove that the *not* symbols are also eliminated. The matching equations containing only ground terms are clearly reduced to either  $\top$  or  $\perp$  and further eliminated. The variables under the *not* symbol can be of two types: quantified — which will be eliminated by the rule `Exists1` — and not quantified. In this case, it means that they were not under a  $\top$  symbol, and therefore they are free variables that we can find in the context of *not*. In other words, for any  $x_i \prec_{\mathcal{AU}} t_i$  under the *not* symbol, where  $x_i$  is not universally quantified, there exists a corresponding  $x_i \prec_{\mathcal{AU}} t_i$  in the context. Given that, the rule `Replacement` will transform the equations under the *not* in simpler equations that will be further reduced to  $\top$ .  $\square$

## F Proof of Proposition 4.4

**Proposition 4.4.** *Given an anti-pattern matching equation  $q \prec_{\mathcal{AU}} t$ , with  $q \in \text{PureFVars}$ , the application of  `$\mathcal{AU}$ -AntiMatchingEfficient` is sound and preserving.*

*Proof.* The most interesting rule is `Mutate`. First, let us prove the pre-serving property:  $\sigma \in \text{Sol}(f(p_1, p_2) \prec_{\mathcal{AU}} f(t_1, t_2))$  implies from Definition 4.3 that  $f(t_1, t_2) \in \llbracket f(\sigma(p_1), \sigma(p_2)) \rrbracket_{g\mathcal{AU}}$ , with  $\sigma \in \mathcal{GS}(f(p_1, p_2)) \Rightarrow \exists t \in \llbracket f(\sigma(p_1), \sigma(p_2)) \rrbracket_g$  such that  $f(t_1, t_2) =_{\mathcal{AU}} t$ . But  $t \in \llbracket f(\sigma(p_1), \sigma(p_2)) \rrbracket_g$  implies that  $t = f(u, v)$ , where  $u \in \llbracket \sigma(p_1) \rrbracket_g$  and  $v \in \llbracket \sigma(p_2) \rrbracket_g$ . Furthermore,  $f(t_1, t_2) =_{\mathcal{AU}} f(u, v)$  is equivalent (from Proposition 3.3) with  $(t_1 =_{\mathcal{AU}} u \wedge t_2 =_{\mathcal{AU}} v) \vee \exists x(t_2 =_{\mathcal{AU}} f(x, v) \wedge f(t_1, x) =_{\mathcal{AU}} u) \vee \exists x(t_1 =_{\mathcal{AU}} f(u, x) \wedge f(x, t_2) =_{\mathcal{AU}} v)$ . But  $u \in \llbracket \sigma(p_1) \rrbracket_g$  and  $v \in \llbracket \sigma(p_2) \rrbracket_g$ , and therefore we have that  $(t_1 \in \llbracket \sigma(p_1) \rrbracket_g \wedge t_2 \in \llbracket \sigma(p_2) \rrbracket_g) \vee (t_2 \in \llbracket \sigma(f(x, p_2)) \rrbracket_g \wedge f(t_1, x) \in \llbracket \sigma(p_1) \rrbracket_g) \vee (t_1 \in \llbracket \sigma(f(p_1, x)) \rrbracket_g \wedge f(x, t_2) \in \llbracket \sigma(p_2) \rrbracket_g)$  which means exactly that  $\sigma$  is the solution of the right-hand side of our initial equation, except for the fact that  $\sigma \in \mathcal{GS}(f(p_1, p_2))$  and we need other domains for  $\sigma$ . For instance, for  $t_1 \in \llbracket \sigma(p_1) \rrbracket_g$  we need that  $\sigma \in \mathcal{GS}(p_1)$ . But this is immediately implied by the restriction of the class `PureFVars`, because it is not possible to have

a variable that is free in  $f(p_1, p_2)$  and not free in  $p_1$ . Therefore  $\sigma \in \mathcal{GS}(f(p_1, p_2))$  is equivalent with  $\sigma \in \mathcal{GS}(p_1)$  when applying  $\sigma$  on  $p_1$ . Consequently, we have that the rule preserves the solutions. The soundness follows the same reasoning. The proof for the rest of the rules is trivial.  $\square$