

Efficient temporal pointcuts through dynamic advice deployment

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ABSTRACT

In previous work we and others have studied the applicability of various trace based matching approaches such as tracematches [2], tracecuts [15] and tracechecks [6, 14, 5] (through our prototype tool J-LO, the Java Logical Observer). Such formalisms provide users with an expressive matching language that gives explicit and well-defined access to an application's execution history. In some approaches, even free variables in expressions can dynamically be bound to objects on the execution trace. This avoids having to use data structures such as hash maps or sets in order to implement such object-related properties.

In this work we demonstrate that besides the aforementioned issues of more convenient programming, such temporal pointcuts yield a large potential for possible optimizations through runtime deployment of aspects, due to their well-defined structure. Functionally equivalent code in pure AspectJ would not necessarily yield such a potential. This feature of trace languages adds well to static optimizations such as control flow and dataflow analysis as it has been proposed in [2]. We do not want to give a fully fledged end-to-end solution here, which may restrict us to a certain specification formalism or runtime weaving approach. Instead, we show up general potential for optimizations through dynamic deployment as a pointer to future research on the field.

Categories and Subject Descriptors

D.3.3 [Programming Languages]: Language Constructs and Features—*Dynamic storage management*

General Terms

Languages, Performance, Verification, Theory

Keywords

Program monitoring, Aspect-oriented programming, dynamic deployment

1. INTRODUCTION

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In the previous two years, a lot of effort has been put into trace based matching languages, which allow users to match not only based on a *current joinpoint* but also based on information of the *execution history*. Most of those mechanisms are language extensions of AspectJ and here we want to concentrate on those. However, we believe that most other applications which use a formalism for temporal reasoning at runtime could benefit from the insights we provide. In particular, previous workshops in the field of Runtime Verification [1] have shown a growing interest by people of the verification community in aspect-oriented techniques. This is due to the fact that, despite the enormous contributions which have been made to static verification approaches as Model Checking, some properties can still only be checked during runtime of an application under test. Any hybrid technique making use of such checker components at runtime *must* of course induce *some* computational burden. The contribution of this work is to point into directions which promise potential for keeping this computational burden as low as possible.

In section 2 we give examples for trace based matching in different formalisms and compare to manual trace matching in native AspectJ. We then briefly describe how trace matching formalisms are usually implemented and section 3 summarizes the implementation properties they share. This enables us to identify common potential for optimizations through runtime matching (section 4). Then we show that the explicit history access the formalisms provide is crucial to this optimization potential: As we show in section 5, an equivalent aspect in native AspectJ could not easily be optimized in the same way - the optimizations only become possible through the explicit model provided by those formalism. We conclude this work in section 6.

2. TRACE MATCHING APPROACHES

In the following we briefly introduce three approaches to trace matching, based on different formalisms namely regular expressions, linear temporal logic and context free grammars.

2.1 Tracematches

In 2005, Allan et al. introduced tracematches [2], an AspectJ language extension for history based matching based on *regular expressions*. The input to a tracematch is a strict sequence (i.e. multiple symbols holding at the same time are virtually sequentialized) of named *symbols*, each such symbol essentially being a pointcut and a before/after specifica-

```

1 tracematch(Vector c, Enumeration e) {
2     sym create after returning(e): call(Enumeration+.new(..) && args(c);
3     sym next before:           call(Object Enumeration.nextElement()) && target(e);
4     sym update after:         vector_update() && target(c);
5
6     create next* update+ next
7     {
8         throw new ConcurrentModificationException();
9     }
10 }

```

Figure 1: Safe enumeration tracematch

tion. The tracematch is then formed as a regular expression over an alphabet defined by those symbols.

The listing in figure 1 shows a tracematch detecting unsafe use of enumerations: An enumeration should not be used any more as soon as the underlying collection is modified, since in this case the enumeration could skip certain elements or could enumerate elements which are not contained in the collection any more. The tracematch in figure 1 implements a check for this by stating: Whenever an enumerator e is claimed for a vector c (event `create`), the vector is not to be updated (event `update`) as long as this enumeration is in use (i.e. `nextElement` is being called). Line 1 declares free variables c and e , which *each possible* matching instance will be bound to. Lines 2-4 declare the symbol alphabet, while line 6 holds the regular expression in question: Enumeration creation (possibly followed by some calls to `next`) followed by an update of the vector and some call to `next` should trigger an error message.

As one would guess, there might be properties, which may be cumbersome to express with regular expressions, especially safety properties, which state that *something bad should never happen*. Such a statement makes use of some implicit negation, which in regular expressions can only be implemented by converting the property to a regular expression *enumerating* the language of all possible path violating this property.

2.2 Tracechecks

Our own previous work was inspired by static and dynamic *verification* tools and was first developed as an independent effort. We explicitly provide negation and conjunction, introducing another specification formalism over pointcuts based on linear temporal logic (LTL), called *tracechecks*. As tracematches, it features dynamic bindings of free variables. Besides, it is equal to usual LTL [12] with temporal operators **X** (next), **F** (finally), **G** (globally), **U** (until) and **R** (release). This logic can then be used to specify temporal assertions, which have to hold during each execution of the given application. Any violation of such a trace condition is reported at runtime. Our research prototype J-LO implements tracechecks, currently in a purely dynamic way.

Figure 2 gives an example specification stating that always (**G**) after a collection c has been added to a hash set s , this collection should not be modified on the subsequent path, unless (**R**) it was removed from the hash set again.

2.3 Context-free patterns

There are other approaches around (e.g. tracecuts [15],

PQL [11]) which allow for even more expressiveness, in particular for context-free patterns. We do not want to explain those in depth here, because handling of such features would lead us out of the scope of this paper. Section 4.5 however explains the rough idea of how our observations could possibly be of similar use to such formalism.

3. COMMON ASPECTS OF TRACE MATCHING

The aforementioned approaches, despite providing relatively different specification formalisms, share quite some implementation details. The available implementations of tracematches and tracechecks for example both use finite automata to propagate state over time. An implementation allowing for the specification of context-free expressions however might need to employ a pushdown automaton (stack machine) depending on the kind of pattern. Yet, all those automata, irrespective the fact of being finite or infinite are *triggered in the same way* - through declared symbols (pointcuts) in AspectJ: A transition is only triggered at well-defined join points, which need to be exposed by the AOP runtime that is employed.

This fact yields optimization potential through dynamic aspect deployment: Maybe the mindful reader has noticed in our examples already that *not all* such symbols may actually trigger a state transition *at any time*.

Take for example the tracematch about “safe enumeration”: Here, between `create` and `update`, it does not matter whether there are zero, one or multiple occurrences of `next` — the pattern would match either way. We say that `next` is *irrelevant* in this state.

Or take the tracecheck checking for safe use of hash sets: It does not matter to us whether a collection is actually modified or removed from a hash set unless it was added to a hash set before. Hence, our conclusion is that not every declared symbol is of interest at any time. Consequently, in those states the associated joinpoints should not even trigger an event in order to achieve an improved performance. This can and should be achieved by dynamic advice enablement.

But how can we algorithmically determine the set of relevant or irrelevant symbols? We give initial pointers to answering this question in the next section.

4. DETERMINING THE SYMBOLS OF INTEREST

Symbols of interest are those symbols which are able to change the internal state of a trace matching automaton —

```

1 tracecheck(Collection c, HashSet s) {
2   sym add after:      call(* HashSet+.add(..)) && target(s) && args(c);
3   sym remove before: call(* HashSet+.remove(..)) && target(s) && args(c);
4   sym modify before: (
5     call(* Collection+.add*(..)) ||
6     call(* Collection+.remove*(..)) ||
7     call(* Collection+.clear())
8   ) && target(c);
9
10  G( add  $\rightarrow$  (remove R !modify) )
11  {
12    throw new ModifiedHashCodeException();
13  }
14 }

```

Figure 2: Tracecheck ensuring safe use of hash sets

whatever this automaton might look like. By *state* we here refer to the full configuration of the automaton, i.e. in the case of stack-based automata, the stack content has to be taken into account for those considerations.

In the following we will however first explain the easier case where *finite* automata are involved. This covers the implementations of tracematches and tracechecks and might also apply to special cases of more expressive implementations. We will cover such systems further in section 4.5.

4.1 Regular expressions

The use of regular expressions leads naturally to finite automata, which are usually deterministic but sometimes also determinized on-the-fly for enhanced efficiency. Here the notion of an irrelevant transition is easy as we can see in our example tracematch.

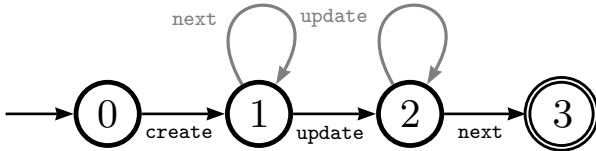


Figure 3: Finite automaton for safe enumeration tracematch of figure 1

Figure 3 shows the (nondeterministic) finite automaton for the “safe enumeration” tracematch. (We abstract from *skip* transitions as they are mentioned in [2] because they do not contribute to, nor interfere with, the analysis we describe here.) Taking into account that *loops* in an automaton do not change state, all those (here shown in grey) can safely be dropped, still yielding the same semantics. For example, in state 1, it would make no difference if there occurred a call to the *next* method of the associated enumeration.

Consequently, the associated joinpoints can be dynamically deactivated when such a state is reached. This leaves us for this example with the following *relevant* symbols for each state:

state	relevant symbols
0	{create}
1	{update}
2	{next}
3	\emptyset

In the following, we will denote this relationship by the function $rel : Q \rightarrow 2^\Sigma$ which returns for each state the set of relevant input symbols. Formally, for an alphabet Σ , a state set Q and a transition relation Δ , we define

$$rel(q) := \{s \in \Sigma \mid \exists q' \in Q . q \neq q' \wedge (q, s, q') \in \Delta\}.$$

4.2 Dynamic deployment

Based on this information, we can now augment our original automaton with dynamic deployment commands:

- **deploy**(s) - Deploy advice associated to $s \in \Sigma$ so that symbol s can be triggered.
- **undeploy**(s) - Undeploy advice for s respectively.

We define the set of all such commands as:

$$C_\Sigma := \{\text{deploy}(s), \text{undeploy}(s) \mid s \in \Sigma\}$$

Note that when using the term *deployment* we refer to both, dynamic (un)weaving of code and dynamic aspect disablement (e.g. by the means of Boolean flags). In general, both approaches can be used interchangeably. What method is suitable for a given application depends on the application that is instrumented and on the weaver infrastructure. Here we do not discuss the impact of such tradeoffs. We live this to future work.

This yields an enriched finite automaton with a labeling function $comm : Q \rightarrow 2^{C_\Sigma}$, which associates each state $q \in Q$ with the set of necessary deployment commands: Let q_p be the previous state observed, then in each state we deploy advice for those symbols which are relevant but have not been relevant before and we undeploy those symbols which have been relevant in q_p but are now not relevant any more.

$$\begin{aligned}
comm(q) = & \{\text{deploy}(s) \mid s \in rel(q) \wedge s \notin rel(q_p)\} \\
& \cup \{\text{undeploy}(s) \mid s \notin rel(q) \wedge s \in rel(q_p)\}
\end{aligned}$$

Note that this function can be statically precalculated. Yet this procedure may lead to relatively frequent (un)deployment. This might not be a problem, especially in environments, where such (un)deployment can be performed reasonably fast. However, depending on the overhead this (un)deployment may induce, one might want to use a larger window instead, i.e. one would undeploy a symbol only if it is irrelevant and has been so for the last n states. The exact parameters will

of course heavily depend on the infrastructure in operation. Hence we leave it as open work for other researchers to find suitable parameters for how long such a history should be kept for best performance of the targeted system. For our example from above, the command function would look at follows:

state q	deployment command $comm(q)$
0	{ <code>deploy(create)</code> }
1	{ <code>undeploy(create), deploy(update)</code> }
2	{ <code>undeploy(update), deploy(next)</code> }
3	{ <code>undeploy(next)</code> }

Those commands are obviously to be applied immediately upon arrival at q .

4.3 The case of temporal logic

In temporal logic, it is more often desired that certain events are ignored (as e.g. noted in [2, 5]). LTL semantics take this into account. For instance the abstract LTL formula $\mathbf{G}(p \rightarrow \mathbf{F}q)$ requires *one* event q to follow whenever p is seen — it specifies nothing at all about events that could happen in between. Consequently, any path where always p is followed by q would satisfy the formula. But let us now consider the concrete example from before.

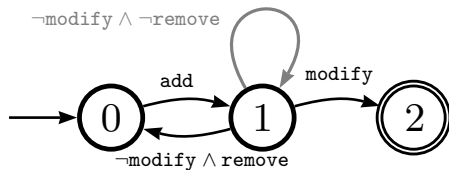


Figure 4: Finite automaton for hash set tracecheck of figure 2

Figure 4 shows a finite automaton implementing the check for our hash set example formula (cf. figure 2). In contrast to regular expressions as they are used in tracematches, LTL is *propositional*, i.e. it can distinguish between different propositions holding *at the same time*. (This is not important in this example, but it is, when symbols overlap, i.e. share a common subset of matched joinpoints, which generally can well be the case.) Hence, the input to an LTL formula (or the equivalent automaton) is usually a sequence of *sets of symbols*, i.e. an element of $(2^\Sigma)^*$. This is reflected by transitions with conditions as $\neg\text{modify} \wedge \text{remove}$: This transition is taken when `remove` matches the current joinpoint, but `modify` does not.

As we can easily see, this change in the automaton model does not really affect our previous observations. Still we can determine the set of relevant symbols for any state of the automaton, just as before, now joining over all symbols contributing to a transition. (As for regular expressions, we assume that self-loops have already been eliminated.) Also the command function remains unaffected.

In our hash set example, this would yield the following result:

state q	$rel(q)$	$comm(q)$
0	{ <code>add</code> }	{ <code>undeploy(modify), undeploy(remove), deploy(add)</code> }
1	{ <code>modify, remove</code> }	{ <code>undeploy(add), deploy(modify), deploy(remove)</code> }
2	\emptyset	{ <code>undeploy(modify), undeploy(remove)</code> }

4.4 Per-object deployment

What we did not consider so far is one hidden peculiarity which is common to all the aforementioned formalisms: They all allow to *dynamically bind objects* in their specification. In other words, taking our LTL formula into account, the structure of the formula is not just

$$\mathbf{G}(\text{add} \rightarrow (\text{remove } \mathbf{R} \neg\text{modify}))$$

but rather:

$$\forall h \forall c : \mathbf{G}(\text{add}(h, c) \rightarrow (\text{remove}(h, c) \mathbf{R} \neg\text{modify}(c)))$$

So in order to apply the above deployment correctly, one would have to modify the command function accordingly:

state q	$rel(q)$	$comm(q)$
0	{ <code>add(h, c)</code> }	{ <code>undeploy(modify, (c)), undeploy(remove, (h, c)), deploy(add, (h, c))</code> }
1	{ <code>modify(c), remove(h, c)</code> }	{ <code>undeploy(add, (h, c)), deploy(modify, (c)), deploy(remove, (h, c))</code> }
2	\emptyset	{ <code>undeploy(modify, (c)), undeploy(remove, (h, c))</code> }

Such instance based deployment has been around for a long time, for instance in the Common Lisp Object System (CLOS) [3]. We are currently aware of one application, namely Steamloom [10, 4], which provides such instance-based advice deployment for Java. Certainly such support would most sensibly have to be integrated into the virtual machine in use.

4.5 More expressiveness: Stacks and counters

When moving from regular expressions to more expressiveness, the natural step is usually the one to context free grammars (CFGs), which might lead to the necessity of bookkeeping state on a stack during runtime. Tracecuts for example is one system with this property.

Again, we don't want to go into detail here, but instead we want to point to the important fact that *reachability* is decidable for CFGs: See [8] for an algorithm that describes how reachability can be decided for those in polynomial time.

4.6 Applicability to non-AOP approaches

As mentioned above, several tools exist, especially in the Runtime Verification community, which are not directly related to the use of aspects or to aspect-oriented programming at all. Instead they seek to verify certain program properties at runtime. Yet, such tools could naturally benefit from our observations as those might be able to gain speedup by dynamic (un)weaving of employed instrumentation in the very same way. PQL [11], PTQL [13], HAWK [7], and EAGLE [9] are for instance some candidates which could benefit from such efforts.

5. THE CASE OF PURE ASPECTJ

The purpose of this section is to show that formalisms as the one above, which *explicitly* match on the execution history of an application, is essential to the analyses we provide in this work.

Assume again the example of assuring safe enumeration, as it was conducted using tracematches. Assume further, one would have tried to implement the same functionality in pure AspectJ. One would have had no other option than generating an aspect containing at least three pieces of advice (one each for `create`, `update` and `next`) and then using those pieces of advice to conduct state transitions within the aspect. Figure 5 shows an excerpt of some pseudo implementation as it would be necessary. As one would guess, an analysis of such an aspect for any temporal properties is in the general case impossible. Since the temporal structure is now “flattened” into independent pieces of advice, every potential for analysis of the temporal behavior is gone. Hence we argue that the abovementioned approaches for a formal, explicit specification of temporal properties are indeed *necessary* to allow for such analyses in the first place.

```
1 aspect SafeEnum {
2   after(Vector c) returning(Enumeration e):
3     call(Enumeration+.new(..) && args(c) {
4       if(in state 0) {
5         take transition to state 1,
6         storing c and e
7       }
8     }
9   before(Vector c):
10    vector_update() && target(c) {
11      if(in state 2 for object c) {
12        take transition to state 3 for c
13      }
14    }
15    //advice for 3rd symbol "next" here
16 }
```

Figure 5: Safe enumeration tracematch

6. CONCLUSION

In this work we have shown an overview of how properties of temporal specification languages can be exploited for the purpose of efficiency gains through dynamic advice deployment. Such history based matching languages, opposed to pure AspectJ, expose an explicit temporal structure in their matching constructs in order to match event patterns in the execution history of a running application. This temporal structure could successfully be shown to be rich enough to allow for an improved runtime performance by temporarily, dynamically unweaving parts of the matching machinery.

We have shown that this approach is applicable to regular expressions and linear temporal logic (LTL) and to the tools implementing pointcuts based on those formalisms, namely tracematches and tracechecks / J-LO. Furtheron, we described how the mechanism could possibly be extended to more expressive formalisms making use of stacks and counters.

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