Specification Matching of Software Components

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Abstract

Specification matching is a way to compare two software components based on descriptions of the components' behaviors. In the context of software reuse and library retrieval, it can help determine whether one component can be substituted for another or how one can be modified to fit the requirements of the other. In the context of object-oriented programming, it can help determine when one type is a behavioral subtype of another.

We use formal specifications to describe the behavior of software components, and hence, to determine whether two components match. We give precise definitions of not just exact match, but more relevantly, various flavors of relaxed match. These definitions capture the notions of generalization, specialization, and substitutability of software components.

Since our formal specifications are pre- and post-conditions written as predicates in firstorder logic, we rely on theorem proving to determine match and mismatch. We give examples from our implementation of specification matching using the Larch Prover.

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1. Motivation and Introduction

Specification matching is a process of determining if two software components are related. It underlies understanding this seemingly diverse set of questions:

- *Retrieval.* How can I retrieve a component from a software library based on its semantics, rather than syntactic structure?
- *Reuse*. How might I adapt a component from a software library to fit the needs of a given subsystem?
- Substitution. When can I replace one software component with another without affecting the observable behavior of the entire system?
- Subtype. When is an object of one type a subtype of another?

In retrieval, we search for all library components that satisfy a given query. In reuse, we adapt a component to fit its environmental constraints, based on how well the component meets our requirements. In substitution, we expect the behavior of one component to be observably equivalent to the other's; a special case of substitution is when a subtype object is the component substituting for the supertype object. Common to answering these questions is deciding when one component *matches* another, where "matches" generically stands for "satisfies," "meets," or "is equivalent to." Common to these kinds of matches is the need to characterize the dynamic behavior, i.e., semantics, of each software component.

It is rarely the case that we would want one component to match the other "exactly." In retrieval, we want a close match; as in other information retrieval contexts [SM83, ML94, OKS⁺93], we might be willing to sacrifice precision for recall. That is, we would be willing to get some false positives as long as we do not miss any (or too many) true positives. In determining substitutability, we do not need the substituting component to have the exact same behavior as the substituted, only the same behavior relative to the environment that contains it.

In this paper we lay down a foundation for different kinds of semantic matches. We explore not just *exact match* between components, but many flavors of *relaxed match*. To be concrete and to narrow the focus of what match could mean, we make the following assumptions:

- The software components in which we are interested are *functions* (e.g., C routines, Ada procedures, ML functions) and *modules* (roughly speaking, sets of functions) written in some programming language. These components might typically be stored in a program library, shared directory of files, or software repository.
- Associated with each component, C, is a signature, C_{sig} , and a specification of its behavior, C_{spec} .

Whereas signatures describe a component's type information (which is usually statically-checkable), specifications describe the component's dynamic behavior. Specifications more precisely characterize the semantics of a component than just its signature. In this paper, our specifications are formal, i.e., written in a formally defined assertion language.

Given two components, $C = \langle C_{sig}, C_{spec} \rangle$ and $C' = \langle C'_{sig}, C'_{spec} \rangle$, we define a generic component match predicate, *Match*:

Definition 1 (Component Match)

 $\begin{array}{l} Match: \text{ Component, Component} \to \text{Bool} \\ Match(C,C') = \\ match_{sig}(C_{sig},C'_{sig}) \land match_{spec}(C_{spec},C'_{spec}) \end{array}$

Two components C and C' match if 1) their signatures match, given some definition of signature matching, and 2) their specifications match, given some definition of specification match. Although we define match as a conjunction, we can think of signature match as a "filter" that eliminates the obvious non-matches before trying the more expensive specification match.

There are many possible definitions for the signature match predicate, $match_{sig}$, which we thoroughly analyzed in a previous paper [ZW95]. In the remainder of this paper, for $match_{sig}$, we use for functions type equivalence modulo variable renaming ("exact match" in [ZW95]), and for modules, a partial mapping of functions in the modules with exact signature match on the functions ("generalized module match" in [ZW95]).

In this paper, we focus on the specification match predicate, $match_{spec}$. We write pre-/postcondition specifications for each function, where assertions are expressed in a first-order predicate logic. We determine match between two functions by some logical relationship, e.g., implication, between the two pre-/post-condition specifications. We modularly define match between two modules in terms of some kind of match between corresponding functions in the modules. Given our choice of formal specifications, we exploit state-of-the-art theorem proving technology as a way to implement a specification match engine. All of the example matches in this paper have been proven using the LP theorem prover[GG91].

Specification match goes a step beyond signature match. For functions, signature match is based entirely on the functions' types, e.g., $int * int \rightarrow int$, and not at all on their behavior. For example, integer addition and subtraction both have the same signature, but completely opposite behavior; the C library routines *strcpy* and *strcat* have the same signature but users would be unhappy if one were substituted for the other. Given a large software library or a large software system, many functions will have identical signatures but very different behavior. For example, in the C math library nearly two-thirds of the functions (31 out of 47) have signature *double* \rightarrow *double*. Based on signature match alone, we cannot know which of a large number of retrieved functions does what we want. Since specification match takes into consideration more knowledge about the components it allows us to increase the precision with which we determine when two components match.

For each kind of match we define, there is both a match name and a match predicate symbol. For example, the strongest function specification match is named *exact pre/post match* and has the predicate symbol $match_{E-pre/post}$. For each match named M with the predicate symbol $match_M$ and components S and Q, if $match_M(S, Q)$ holds, we say equivalently:

- M match of S with Q
- S matches with Q (under M)
- Q is matched by S (under M)

It is important to distinguish between "matches with" and "is matched by", because not all matches are symmetric: $match_M(S,Q)$ does not necessarily imply that $match_M(Q,S)$. For the matches that are symmetric, we also say that "S and Q satisfy the match."

In what follows, we first briefly describe the language with which we write our formal specifications. We define exact and relaxed match for functions (Section 3) and then for modules (Section 4). We discuss our implementation of a specification matcher using the Larch Prover in Section 5 and two applications of specification match in the software engineering context in Section 6. We close with related work and a summary.

2. Larch/ML Specifications

We use Larch/ML [WRZ93], a Larch interface language for the ML programming language, to specify ML functions and ML modules. Larch provides a "two-tiered" approach to specification [GH93]. In one tier, the specifier writes *traits* in the Larch Shared Language (LSL) to assert state-independent properties. Each trait introduces *sorts* and *operators* and defines equality between terms composed of the operators (and variables of the appropriate sorts). Appendix 1 shows the *OrderedContainer* trait. Ordered containers are multisets that maintain an ordering on elements based on time of insertion (i.e., there is a notion of a first and last element). Elements are also ordered by a total order, >, on their values, e.g., integral values. Counter to the Larch style of using different traits for different theories, we chose to use the single trait *OrderedContainer* in multiple ways in order to simplify the explanations of our examples. The trait defines operators to generate containers (*empty* and *insert*), to return the container resulting from deleting a particular element (*delete*), to return the element or container resulting from deleting the first or last element (*first, last, butFirst, and butLast*), and to return information about a container (*size, isEmpty*), information about a particular element (*isIn, count*), and the maximum element of a container according to the total ordering on elements (*max*).

In the second tier, the specifier writes *interfaces* in a Larch interface language to describe state-dependent effects of a program (see Figure 1). The Larch/ML interface language extends ML by adding specification information in special comments delimited by $(* + \ldots + *)$. The using and based on clauses link interfaces to LSL traits by specifying a correspondence between (programming-language specific) types and LSL sorts. For polymorphic sorts, there must be an associated sort for both the polymorphic variable (e.g., α) and the type constructor (e.g., T) in the **based on** clause. The specification for each function begins with a *call pattern* consisting of the function name followed by a pattern for each parameter, optionally followed by an equal sign (=)and a pattern for the result. In ML, patterns are used in binding constructs to associate names to parts of values (e.g., (x, y)) names x as the first of a pair and y as the second). The requires clause specifies the function's pre-condition as a predicate in terms of trait operators and names introduced by the call pattern. Similarly, the **ensures** clause specifies the function's post-condition. If a function does not have an explicit **requires** clause, the default is **requires** *true*. A function specification may also include a **modifies** clause, which lists those objects whose values may change as a result of executing the function. Larch/ML also includes rudimentary support for specifying higher-order functions.

Though simplistic, for exposition purposes, we will use the Larch/ML interface specifications

```
signature Stack = sig
                                                              signature Queue = sig
  (*+ using OrderedContainer +*)
                                                                (*+ using OrderedContainer +*)
 type \alpha t (*+ based on
                                                                type \alpha t (*+ based on
    OrderedContainer. E OrderedContainer. (+*)
                                                                  OrderedContainer.E OrderedContainer.C +*)
 val create : unit \rightarrow \alpha t
                                                                val create : unit \rightarrow \alpha t
 (*+ create () = s
                                                                (*+ create()) = q
    ensures s = empty + *
                                                                   ensures q = empty + *
 val push : \alpha \ t * \alpha \to \alpha \ t
                                                                val enq: \alpha t * \alpha \to \alpha t
 (*+push (s,e) = s2
                                                                (*+ enq (q, e)) = q2
    ensures s2 = insert(e, s) + *
                                                                   ensures q2 = insert(e,q) + *
 val pop : \alpha \ t \to \alpha \ t
                                                                val rest : \alpha \ t \to \alpha \ t
 (*+pop \ s = s2)
                                                                (*+ rest q = q2)
    requires not(isEmpty(s))
                                                                  requires not(isEmpty(q))
    ensures s2 = butLast(s) + *
                                                                  ensures q2 = butFirst(q) + *
 val top : \alpha \ t \to \alpha
                                                                val deq: \alpha t \to \alpha
 (*+top \ s = e
                                                                (*+ deq q = e
    requires not(isEmpty(s))
                                                                   requires not(isEmpty(q))
    ensures e = last(s) + *
                                                                   ensures e = first(q) + *
end
                                                              end
```

Figure 1: Two Larch/ML Specifications

of Figure 1 as the "library" for our examples of specification matching. It contains two module specifications: one for *Stack* with the functions *create*, *push*, *pop*, and *top*, and one for *Queue*, with the functions *create*, *enq*, *rest*, and *deq*. We specify each function's pre- and post-conditions in terms of operators from the *OrderedContainer* trait (shown in Appendix A).

3. Function Matching

For a function specification, S, we denote the pre- and post-conditions as S_{pre} and S_{post} , respectively. S_{pred} defines the interpretation of the function's specification as an implication between the two: $S_{pred} = S_{pre} \Rightarrow S_{post}$. This interpretation means that if S_{pre} holds when the function specified by Sis called, S_{post} will hold after the function has executed (assuming the function terminates). If S_{pre} does not hold, there are no guarantees about the behavior of the function. This interpretation of a pre- and post-condition specification is the most common and natural for functions in a standard programming model. For example, for the Stack *top* function in Figure 1

- The pre-condition top_{pre} is not(isEmpty(s)).
- The post-condition top_{post} is e = last(s).
- The specification predicate top_{pred} is $(not(isEmpty(s))) \Rightarrow (e = last(s)).$

To be consistent in terminology with our signature matching work, we present function specification matching in the context of a retrieval application. Example matches are between a library specification S and a query specification Q. We assume that variables in S and Q have been

Match	Predicate Symbol	\mathcal{R}_1	\mathcal{R}_2	\widehat{S}
Exact Pre/Post Plug-in Plug-in Post Guarded Plug-in Guarded Post	$match_{E-pre/post}$ $match_{plug-in}$ $match_{plug-in-post}$ $match_{guarded-plug-in}$ $match_{guarded-post}$	$\begin{array}{c} \Leftrightarrow \\ \Rightarrow \\ * \\ \Rightarrow \\ * \\ * \\ * \\ * \\ \end{array}$	$\begin{array}{c} \Leftrightarrow \\ \Rightarrow \\ \Rightarrow \\ \Rightarrow \\ \Rightarrow \\ \Rightarrow \\ dropped \end{array}$	S_{post} S_{post} S_{post} $S_{pre} \wedge S_{post}$ $S_{pre} \wedge S_{post}$

Table 1: Instantiations of generic pre/post match $((Q_{pre} \mathcal{R}_1 S_{pre}) \land (\widehat{S} \mathcal{R}_2 Q_{post}))$

renamed consistently¹. For example, if we compare the Stack *pop* function with the Queue *rest* function, we must rename q to s and q^2 to s^2 . The examples presented in this section are intended primarily as illustrations of the various match definitions. Additional examples of more practical applications appear in Section 6. In this section we examine several definitions of the specification match predicate (*match_{spec}(S,Q)*). We characterize definitions as either grouping pre-conditions S_{pre} and Q_{pre} together and post-conditions S_{post} and Q_{post} together, or relating predicates S_{pred} and Q_{pred} . Both of these kinds of matches have a general form.

Definition 2 (Generic Pre/Post Match)

$$match_{pre/post}(S,Q) = (Q_{pre} \ \mathcal{R}_1 \ S_{pre}) \ \land \ (\widehat{S} \ \mathcal{R}_2 \ Q_{post})$$

Pre/post matches relate the pre-conditions of each component and the post-conditions of each component. Post-conditions of related functions are often similar, so we want to compare them directly to each other. For example, post-conditions may specify related properties of the return values. Similarly, pre-conditions of related functions may specify related bounds conditions of input values. In some cases, we may want to include some information about the pre-condition in the post-condition clause. To allow this flexibility, we let \hat{S} be either S_{post} or $S_{pre} \wedge S_{post}$ in the generic pre/post match definition. The relations \mathcal{R}_1 and \mathcal{R}_2 relate pre-conditions and post-conditions respectively, and are either equivalence (\Leftrightarrow) or implication (\Rightarrow), but need not be the same. The matches may vary from this form by dropping some of the terms. Table 1 summarizes how $\mathcal{R}_1, \mathcal{R}_2$, and \hat{S} are instantiated for each of the pre/post matches in Section 3.1. For example, for plug-in match, \mathcal{R}_1 and \mathcal{R}_2 are both \Rightarrow and \hat{S} is S_{post} , so match_{plug-in} is ($Q_{pre} \Rightarrow S_{pre}$) \land ($S_{post} \Rightarrow Q_{post}$). For match_{plug-in-post} and match_{guarded-post}, $\hat{\mathcal{R}}_1$ is not instantiated because its arguments are dropped. For match_{guarded-plug-in} and match_{guarded-post}, \hat{S} is $S_{pre} \land S_{post}$.

Definition 3 (Generic Predicate Match)

 $match_{pred}(S,Q) = S_{pred} \mathcal{R} Q_{pred}$

¹This renaming is easily provided by signature matching; we are assuming that the signatures of S and Q match.

Predicate matches relate the specification predicates, S_{pred} and Q_{pred} , in their entirety. Predicate matches are useful in cases where we need to consider the relationship of the specifications as a whole rather than relationships of the parts, for example, when we need to assume something from the pre-condition in order to reason about post-conditions. Additionally, these definitions apply for specifications of other forms (e.g., for specifications that do not have separate pre- and post-conditions). The relation \mathcal{R} between the specification predicates is equivalence (\Leftrightarrow) for the strictest match, but may be relaxed to either implication (\Rightarrow) or reverse implication (\Leftarrow). Table 2 summarizes how \mathcal{R} is instantiated for each of the predicate matches in Section 3.2.

Match	Predicate Symbol	${\cal R}$
Exact Predicate Generalized Specialized	$match_{E extsf{-}pred}\ match_{gen extsf{-}pred}\ match_{spcl extsf{-}pred}$	↑ ↓ ↓

Table 2: Instantiations of generic predicate match $(S_{pred} \mathcal{R} Q_{pred})$

It is important to look at both pre/post matches and predicate matches. Which kind of match is appropriate may depend on the context in which the match is being used or on the specifications being compared. We present the pre/post matches in Section 3.1 and the predicate matches in Section 3.2. For each, we present a notion of exact match as well as relaxed matches.

3.1. Pre/Post Matches

Pre/post matches on specifications S and Q relate S_{pre} to Q_{pre} and S_{post} to Q_{post} . Each match is an instantiation of the generic pre/post match (Definition 2). We consider five kinds of pre/post matches, beginning with the strongest match and weakening the match by relaxing the relations \mathcal{R}_1 and \mathcal{R}_2 from \Leftrightarrow to \Rightarrow , by adding S_{pre} to \hat{S} , or by dropping the pre-condition term. In each case, relaxing the match allows us to make comparisons between less closely related components, but weakens the guarantees about the relationship between the two components. For example, dropping the pre-condition term would allow us to relate components that have the same behavior for the subset of inputs that they handle but that make different assumptions about which inputs are valid (e.g., routines on arrays with different bounds). However, since we are not comparing the pre-conditions at all, we cannot guarantee that the components are behaviorally equivalent for all inputs.

3.1.1. Exact Pre/Post Match

If exact pre/post match holds for two specifications, the components are essentially equivalent and thus completely interchangeable. Anywhere that one component is used, it could be replaced by the other with no change in observable behavior. Exact pre/post match instantiates both \mathcal{R}_1 and

 \mathcal{R}_2 to \Leftrightarrow and \hat{S} to S_{post} in the generic pre/post match of Definition 2; two function specifications satisfy the *exact pre/post match* if their pre-conditions are equivalent and their post-conditions are equivalent.

Definition 4 (Exact Pre/Post Match)

$$match_{E-pre/post}(S,Q) = (Q_{pre} \Leftrightarrow S_{pre}) \land (S_{post} \Leftrightarrow Q_{post})$$

Exact pre/post match is a strict relation, yet two different-looking specifications can still satisfy the match. Consider for example the following query Q1, based on the *OrderedContainer* trait. Q1 specifies a function that returns an ordered container whose size is zero, one way of specifying a function to create a new ordered container.

```
signature Q1 = sig (Q1)

(*+ using OrderedContainer +*)

type \alpha t based on OrderedContainer.E OrderedContainer.C +*)

val qCreate : unit \rightarrow \alpha t

(*+ qCreate () = c

ensures size(c) = 0 +*)

end
```

Under exact pre/post match, Q1 is matched by both the Stack and Queue *create* functions of Figure 1. (The specifications of Stack and Queue *create* are identical except for the name of the return value.)

Let us look in more detail at how the Stack create specification matches with Q1. Let S be the specification for Stack create and Q1 be the query specification with c renamed to s. S_{pre} = true, $S_{post} = (s = empty)$. $Q1_{pre} = true$, $Q1_{post} = (size(s) = 0)$. Since both S_{pre} and $Q1_{pre}$ are true, showing $match_{E-pre/post}(S,Q1)$ reduces to proving $S_{post} \Leftrightarrow Q1_{post}$, or $(s = empty) \Leftrightarrow$ (size(s) = 0). The "if" case $((s = empty) \Rightarrow (size(s) = 0))$ follows immediately from the axioms in the OrderedContainer trait about size. Proving the "only-if" case $((size(s) = 0) \Rightarrow (s = empty))$ requires only basic knowledge about integers and the fact that for any ordered container, s, $size(s) \ge$ 0, which is provable from the OrderedContainer trait.

3.1.2. Plug-in Match

Equivalence is a strong requirement. Sometimes a weaker match is "good enough." For *plug-in* match, we relax both \mathcal{R}_1 and \mathcal{R}_2 from \Leftrightarrow to \Rightarrow in the generic pre/post match. Under plug-in match, Q is matched by any specification S whose pre-condition is weaker (to allow at least all the conditions that Q allows) and whose post-condition is stronger (to provide a guarantee at least as strong as Q).

Definition 5 (Plug-in Match)

 $match_{plug-in}(S,Q) = (Q_{pre} \Rightarrow S_{pre}) \land (S_{post} \Rightarrow Q_{post})$



Figure 2: Idea Behind Plug-in Match

Plug-in match captures the notion of being able to "plug-in" S for Q, as illustrated in Figure 2. A specifier writes a query Q saying essentially:

I need a function such that if Q_{pre} holds before the function executes, then Q_{post} holds after it executes (assuming the function terminates).

With plug-in match, if Q_{pre} holds (the assumption made by the specifier) then S_{pre} holds (because of the first conjunct of plug-in match). Since we interpret S to guarantee that $S_{pre} \Rightarrow S_{post}$, we can assume that S_{post} will hold after executing the plugged-in S. Finally, since $S_{post} \Rightarrow Q_{post}$ from the second conjunct of plug-in match, Q_{post} must hold, as the specifier desired. We say that S is behaviorally equivalent to Q, since we can plug-in S for Q and have the same observable behavior, but this is not a true equivalence because it is not symmetric: we cannot necessarily plug-in Q for S and get the same guarantees.

Consider the following query. Q2 is fairly weak specification of an *add* function. It requires that the input container has less than 50 elements, and guarantees that the resulting container is one element larger than the input container.

```
signature Q2 = sig (Q2)

(*+ using OrderedContainer +*)

type \alpha t based on OrderedContainer.E OrderedContainer.C +*)

val qEnq: \alpha t * \alpha \rightarrow \alpha t

(*+ qEnq (q1, e) = q2

requires size (q1) < 50

ensures size (q2) = (size (q1) + 1) +*)

end
```

Under exact pre/post match, Q2 is not matched by any function in the library, but under plug-in match, Q2 is matched by both the Stack *push* and the Queue *enq* functions. Since *push* and *enq* are identical except for their names and the names of the variables, the proof of the match is the same for both.

The pre-condition requirement, $Q_{pre} \Rightarrow S_{pre}$, holds, since $S_{pre} = true$. To show that $S_{post} \Rightarrow Q_{post}$, we assume S_{post} (q2 = insert(e,q)), and try to show Q_{post} (size(q2) = size(q) + 1). Substituting for q2 in Q_{post} , we have size(insert(e,q)) = size(q) + 1, which follows immediately from the equations for size.

3.1.3. Plug-in Post Match

If we are concerned with only the effects of functions, then a useful relaxation of the plug-in match is to consider only the post-condition part of the conjunction. (Most pre-conditions could be satisfied by adding an additional check before calling the function.) Plug-in post match is also an instance of generic pre/post match of Definition 2, with \mathcal{R}_2 instantiated to \Rightarrow and \hat{S} instantiated to S_{post} but dropping Q_{pre} and S_{pre} .

Definition 6 (Plug-in Post Match)

 $match_{plug-in-post}(S,Q) = (S_{post} \Rightarrow Q_{post})$

Consider the following query. Q3 is identical to Stack top except that Q3 has no **requires** clause.

```
signature Q3 = sig (Q3)

(*+ using OrderedContainer +*)

type \alpha t based on OrderedContainer.E OrderedContainer.C +*)

val qTop : \alpha t \rightarrow \alpha

(*+ qTop \ c = e

ensures e = last(c) +*)

end
```

Stack top does not match with Q3 under either exact pre/post or plug-in match, because Q3's pre-condition is weaker than Stack top's. Since the post-conditions are equivalent, Stack top does match with Q3 under plug-in post match.

3.1.4. Guarded Plug-in Match

In some cases, the post-condition relation, $S_{post} \Rightarrow Q_{post}$, only holds for values of the input allowed by the pre-condition. For example, the *butFirst* clause mentioned in the post-condition of Stack *pop* is not defined for the empty stack. The guarded plug-in match adds S_{pre} as an assumption (or "guard") to the post-condition relation, to exclude such cases. We instantiate \mathcal{R}_1 and \mathcal{R}_2 to \Rightarrow in the generic pre/post match, as with plug-in match, but we use $\hat{S} = S_{pre} \wedge S_{post}$ rather than $\hat{S} = S_{post}$. We use S_{pre} and not Q_{pre} since S_{pre} is likely to be necessary to limit the conditions under which we try to prove $S_{post} \Rightarrow Q_{post}$.

Definition 7 (Guarded Plug-in)

 $match_{guarded-plug-in}(S,Q) = (Q_{pre} \Rightarrow S_{pre}) \land ((S_{pre} \land S_{post}) \Rightarrow Q_{post})$

For example, suppose we wish to find a function to delete from an ordered container using the following query Q4:

```
signature Q4 = sig (Q4)

(*+ using OrderedContainer +*)

type \alpha t based on OrderedContainer.E OrderedContainer.C +*)

val qRest : \alpha t \rightarrow \alpha t

(*+ qRest c = c2

requires not(isEmpty(c))

ensures size(c2) = (size(c) -1) +*)

end
```

Q4 describes a function that requires a non-empty container and returns a container whose size is one less than the size of the input container. This is a fairly weak way of describing deletion, since it does not specify which element is removed. Even this weak specification match still gives us a big gain in precision over signature matching, however. Q4 would not be matched by other functions with the signature $\alpha t \rightarrow \alpha t$, for example, a function that reverses or sorts the elements in the container, or removes duplicates.

While intuitively Q4 would seem related to Stack *pop* and Queue *rest*, neither *pop* nor *rest* match with Q4 under either plug-in or plug-in post match. Consider Stack *pop* (the reasoning is similar for Queue *rest*). We cannot prove $S_{post} \Rightarrow Q_{post}$ (i.e., $(s2 = butFirst(s)) \Rightarrow (size(s2) = size(s) - 1))$ for the case where s = empty. However, by adding the assumption S_{pre} (not(isEmpty(s))), we are able to show that Stack *pop* matches with Q4 under guarded plug-in match. The first conjunct ($Q_{pre} \Rightarrow S_{pre}$) is trivial, since the pre-conditions of Q4 and Stack *pop* are the same. Figure 3 sketches the proof of the second conjunct ($(S_{pre} \land S_{post}) \Rightarrow Q_{post}$).

Figure 3: Proof Sketch of $match_{guarded-post}(pop, Q4)$

3.1.5. Guarded Post Match

As with plug-in match, we define a more relaxed guarded match by dropping the pre-condition relation term. Because we do not have the pre-condition term, there is no guarantee that S_{pre}

actually holds, so we may have to provide an additional "wrapper" in our code to establish S_{pre} before we call the function specified by S.

Definition 8 (Guarded Post Match)

 $match_{guarded-post}(S,Q) = (S_{pre} \land S_{post}) \Rightarrow Q_{post}$

For example, consider the following query, which is the same as Q4 but without a **requires** clause.

```
signature Q5 = sig (Q5)

(*+ using OrderedContainer +*)

type \alpha t based on OrderedContainer.E OrderedContainer.C +*)

val qRest : \alpha t \rightarrow \alpha t

(*+ qRest c = c2

ensures size(c2) = (size(c) -1) +*)

end
```

Because this query has a stronger pre-condition, it is not matched by any functions in the library under either plug-in or guarded plug-in match. Plug-in post match does not work either because we need to assume S_{pre} (not(isEmpty(s))) to show $S_{post} \Rightarrow Q_{post}$. However, under guarded post match, Q5 is matched by both Stack pop and Queue rest. The proofs are very similar to that for Q4 in the guarded post match (Figure 3).

3.2. Predicate Matches

Recall the generic predicate match (Definition 3):

 $match_{pred}(S,Q) = S_{pred} \mathcal{R} Q_{pred}$

where the relation \mathcal{R} is either equivalence (\Leftrightarrow) , implication (\Rightarrow) , or reverse implication (\Leftarrow) .

Note that this general form allows alternative definitions of the specification predicates. One alternative is $S_{pred} = S_{pre} \wedge S_{post}$, which is stronger than $S_{pred} = S_{pre} \Rightarrow S_{post}$. This interpretation is reasonable in the context of state machines, where the pre-condition serves as a guard so that a state transition occurs only if the pre-condition holds.

As we did with the generic pre/post match, we consider instantiations of the generic predicate match of the generic predicate match including an exact match and various relaxations.

3.2.1. Exact Predicate Match

We begin with *exact predicate match*. Two function specifications match exactly if their predicates are logically equivalent (i.e., \mathcal{R} is instantiated to \Leftrightarrow). This is less strict than exact pre/post match (Definition 4), since there can be some interaction between the pre- and post-conditions (i.e., $match_{E-pre/post} \Rightarrow match_{E-pred}$). In fact, in cases where $S_{pre} = Q_{pre} = true$, exact pre/post and exact predicate matches are equivalent.

Definition 9 (Exact Predicate Match)

$$match_{E\text{-}pred}(S,Q) = S_{pred} \Leftrightarrow Q_{pred}$$

Our example Q1 is still matched by Stack and Queue create under exact predicate match, since

$$S_{pred} \Leftrightarrow Q_{pred} = (true \Rightarrow (s = empty)) \Leftrightarrow (true \Rightarrow (size(s) = 0))$$
$$= (s = empty) \Leftrightarrow (size(s) = 0)$$

which is exactly what we proved to show that Q1 is matched by Stack and Queue *create* under exact pre/post match.

3.2.2. Generalized Match

Generalized match is an intuitive match in the context of queries and libraries: specifications of library functions will be detailed, describing the behavior of the functions completely, but we would like to be able to write simple queries that focus only on the aspect of the behavior that we are most interested in or that we think is most likely to differentiate among functions in the library. Generalized match allows the library specification to be stronger (more general) than the query; \mathcal{R} in the generic predicate match is instantiated to \Rightarrow . Generalized match is a weaker match than plug-in match (i.e., $match_{plug-in} \Rightarrow match_{gen-pred}$).

Definition 10 (Generalized Match)

$$match_{gen-pred}(S, Q) = S_{pred} \Rightarrow Q_{pred}$$

For example, again consider Q4. Using the exact predicate match, neither the Stack *pop* nor the Queue *rest* specifications match with this query. However, under generalized match, Q4 is matched by both of these. The proofs are very similar to that for Q4 in the guarded match (Figure 3).

Consider another example specifying a function that removes the most recently inserted element of an ordered container. This query does not require that the specifier knows the axiomatization of ordered containers, since the query uses only the container constructor, *insert*. The post-condition specifies that the input container, c, is the result of inserting the returned element, e, into another container c2. The existential quantifier (**there exists**) is a way of being able to name c2.

```
signature Q6 = sig (Q6)

(*+ using OrderedContainer +*)

type \alpha t based on OrderedContainer.E OrderedContainer.C +*)

val qTop : \alpha t \rightarrow \alpha

(*+ qTop c = e

requires not(isEmpty(c))

ensures there exists c2:OrderedContainer.C

(c = insert(e, c2)) +*)

end
(Q6)
```

Again, under exact or plug-in matches, Q6 does not retrieve any functions. Under generalized match, the query is matched by the Stack *top* function, but not Queue *deq*, since the query specifies

that the most recently inserted element is returned. To show $match_{gen}(Stack.top, Q6)$, we consider two cases: c = empty, and c = insert(ec, cc). In the first case, the pre-condition for both top and qTop are false, and thus the match predicate is vacuously true. In the second case, the pre-conditions are both true, so we need to prove that $S_{post} \Rightarrow Q_{post}$. If we instantiate c2 to cc, the proof goes through.

3.2.3. Specialized Match

Specialized match is the converse of generalized match: $match_{spcl-pred}(S,Q) = match_{gen-pred}(Q,S)$. A function whose specification is weaker than the query might still be of interest as a base from which to implement the desired function. Specialized match allows the library specification to be weaker than the query; we instantiate \mathcal{R} in the generic predicate match to \Leftarrow .

Definition 11 (Specialized Match)

 $match_{spcl-pred}(S,Q) = Q_{pred} \Rightarrow S_{pred}$

Consider again the query Q3, which is the same as Stack *top* but without the pre-condition. Stack *top* is thus weaker than Q3, but we can show that Q3 implies Stack *top* and hence that Q3 is matched by Stack *top* under specialized match.

3.3. Relating the Function Matches

We relate all our function specification match definitions in a lattice (Figure 4). An arrow from a match M1 to another match M2 indicates that M1 is stronger than M2 (i.e., $M1(S,Q) \Rightarrow M2(S,Q)$ for all S,Q). We also say that M2 is more relaxed than M1.

Table 3 summarizes which of the library functions match each of the six example queries under each of the eight matches we have defined. For example, under generalized match, Q4 is matched by both *Queue.rest* and *Stack.pop*, but under plug-in post match, Q4 is not matched by any functions in the library. Parentheses around a function indicates that the match is implied by a stronger match (e.g., $match_{plug-in}(Q2, Queue.enq) \Rightarrow match_{guarded-plug-in}(Q2, Queue.enq))$.

We define a variety of matches. Which match is most appropriate to use will depend on the particular situation. First, the choice of match depends on the context in which the match is used – how strong of a guarantee is needed about the relation between the two specifications? If we want to know that we can substitute one function for the other and still have the same behavior, we would use plug-in match or an exact match. In contrast, if we are only interested in whether the functions have the same effects and we are willing to check pre-conditions separately, we can use guarded post match. Which match is most appropriate also depends on the actual form of the predicates. In some cases, pre/post matches will be easier to prove with a theorem prover since the pre/post matches relate pre-conditions to pre-conditions and post-conditions to post-conditions, and for two specifications, S and Q, it is likely that S_{pre} and Q_{pre} are related and hence we can reason about that relation (and similarly for S_{post} and Q_{post}). In other cases, however, it is necessary to make some assumptions about the pre-condition in order to prove a relation between the post-conditions. In these cases, the predicate matches are easier to prove.



Figure 4: Lattice of Function Specification Matches

	Exact Pre/Post	Exact Predicate	Plug-in	Guarded Plug-in	Plug-in Post	Special- ized	Gener- alized	Guarded Post
Q1	Q.create S.create	(Q.create) $(S.create)$	(Q.create) (S.create)	(Q.create) $(S.create)$	(Q.create) (S.create)	(Q.create) (S.create)	(Q.create) (S.create)	(Q.create) $(S.create)$
Q2	_		Q.enq S.push	$egin{array}{l} (Q.enq) \ (S.push) \end{array}$	$egin{array}{l} (Q.enq) \ (S.push) \end{array}$	_	$(Q.enq) \ (S.push)$	$egin{array}{l} (Q.enq)\ (S.push) \end{array}$
Q3					S.top	S.top		(S.top)
Q4				Q.rest			(Q.rest)	(Q.rest)
		—	—	S.pop	—	—	(S.pop)	(S.pop)
Q5	—							Q.rest
		—	—	—	—	—	—	S.pop
Q6				S.top			(S.top)	(S.top)

Table 3: Which Ones Match What(where Q = Queue module and S = Stack module)

4. Module Matching

Function matching addresses the problem of matching individual functions. However, a programmer may need to compare collections of functions, for example, ones that provide a set of operations on an abstract data type. Modules, such as Ada packages or C++ classes, are a common language feature of most modern programming languages, and are typically used to support explicitly the definition of abstract data types. Modules are also often used just to group a set of related functions, like I/O routines. This section addresses the problem of matching module specifications.

A module specification interface is a pair, $\Sigma = \langle \Sigma_T, \Sigma_F \rangle$, where

- Σ_T is a set of user-defined types, and
- Σ_F is a set of function abstracts.

 Σ_T introduces the names of user-defined type constructors that may appear in Σ_F . A function abstract is the function name together with the function specification. We include the function name both as useful feedback to the user and to distinguish between abstracts that would otherwise be the same (thus Σ_F is a set rather than a multiset). For example, the *Queue* interface in Figure 1 has one user-defined type ($\Sigma_T = \{\alpha t\}$) and four function abstracts in Σ_F .

For a library interface, $\Sigma_L = \langle \Sigma_{LT}, \Sigma_{LF} \rangle$, to match a query interface, $\Sigma_Q = \langle \Sigma_{QT}, \Sigma_{QF} \rangle$, there must be correspondences both between Σ_{LT} and Σ_{QT} and between Σ_{LF} and Σ_{QF} .

In the module match definition we use here, the user-defined types and function abstracts in the query interface are a subset of those in the library interface. We consider other module match definitions elsewhere [Zar96]. We allow the query interface to be a subset of the library interface so that the querier may specify exactly the functions of interest and match a module that is more general in the sense that its set of functions may properly contain the query's set.

Definition 12 (Module Match)

 $\begin{array}{l} M\text{-}match(\Sigma_L, \Sigma_Q, match_{fn}) = \\ \exists \text{ total functions} \\ U_{TC} : UserOp(\Sigma_{QT}) \rightarrow UserOp(\Sigma_{LT}) \text{ (with corresponding renaming } TC) \text{ and} \\ U_F : \Sigma_{QF} \rightarrow \Sigma_{LF} \\ \text{ such that (1) } U_{TC} \text{ and } U_F \text{ are one-to-one} \\ (2) \forall \tau \in \Sigma_{QT}, match_E(\tau, TC \tau) \\ (3) \forall Q \in \Sigma_{QF}, match_{fn}(U_F(Q), TC Q) \end{array}$

 U_{TC} and TC ensure that user-defined types are named consistently in the two interfaces. For a set of user-defined types Σ_T , $UserOp(\Sigma_T)$ extracts the set of type constructor variables in Σ_T (e.g., for $\Sigma_T = \{\alpha \ T, int \ X\}$, $UserOp(\Sigma_T) = \{T, X\}$). The domain of function U_{TC} is a set of type constructor variables; from it we construct the type constructor renaming sequence TC, which is applied to the signatures of each function specifications in Σ_{QF} . For each $u_q \in UserOp(\Sigma_T)$, the renaming $[U_{TC}(u_q)/u_q]$ appears in TC. To avoid potential naming conflicts, we assume that $UserOp(\Sigma_{QT})$ and $UserOp(\Sigma_{LT})$ are disjoint (if they are not, we can easily make them so).

 U_F maps each query function abstract Q to a corresponding library function abstract, $U_F(Q)$. Since any user-defined types in $U_F(Q)$ come from Σ_{LT} , we apply TC to Q to ensure consistent naming of type constructors. The correspondence between each TC Q and $U_F(Q)$ is that they satisfy the function match, $match_{fn}$. The library module may contain more functions than the query module (i.e., $|\Sigma_{LF}| \ge |\Sigma_{QF}|$, and $\Sigma_{LF} \supseteq TC \Sigma_{QF}$ (where $TC \Sigma_{QF}$ is a shorthand for applying TCto each element of Σ_{QF}). Section 6.2 contains an example of a module match, including a proof of the match relation with LP.

Our definition of module match is highly parameterized and extensible. The function match relation between the pairs of functions is completely orthogonal to the module match definitions; we can instantiate $match_{fn}$ with any of the function specification matches defined in Section 3. In fact, the module match definitions are completely independent of the fact that we are matching specifications at the function level. If we use the same definitions of module matching, but instantiate $match_{fn}$ with a function signature match, we have module signature matching [ZW95].

Most generally, a module interface consists of some global information (Σ_T) and a set of functions (Σ_F) . This framework allows the potential to extend the module interface to contain even more information. For example, we could extend module specification interfaces to include information about shared types or global invariants in Σ_T . A new module match definition including global invariants would be similar to Definition 12, but U_{TC} would change and point (2) of the definition would require some kind of consistency between invariants.

5. Implementation

We use LP, the Larch Prover [GG91], to attempt to prove that a match holds between two specifications. LP is a theorem prover for a subset of multisorted first-order logic. We implemented tools to translate Larch/ML specifications and match predicates into LP input. Each of the specification match examples given in Section 3 (i.e., all entries in Table 3) and in Section 6 have been specified in Larch/ML, translated automatically to LP input, and proven using LP.

For each specification file (e.g., Stack.sig), we check the syntax of the specification and then translate it into a form acceptable to LP. Namely, we generate a corresponding .1p file (e.g., Stack.1p), which includes the axioms from the appropriate LSL trait and contains the appropriate declarations of variables, operators, and assertions (axioms) for the pre- and post-conditions of each function specified. Each function *foo* generates two operators, *fooPre* and *fooPost*; the axioms for *fooPre* and *fooPost* are the bodies of the **requires** and **ensures** clauses of *foo*. Figure 5 shows Stack.1p and Q2.1p, the result of translating the Stack specification from Figure 1 (pg. 5) and the query Q2 (pg. 9) into LP format. The **thaw** *OrderedContainer_Axioms*.1p. We use the 1s1 tool to generate the file OrderedContainer_Axioms.1p from the LSL trait OrderedContainer.1s1. We comment out the **thaw** command in Q2.1p, since we assume that the query (Q2) uses the same trait as the library specification (*Stack*). The command set name Q2 tells LP to use Q2 as the prefix for names of facts and conjectures. Commands **declare var** and **declare op** declare variables and operators that will be used in the axioms. In particular, Q2.1p declares the element variable e,

```
% Stack.lp
%% Using OrderedContainer
thaw OrderedContainer_Axioms
%% signature Stack
set name Stack
declare var
e: E
```

s: C s2: C

•••

declare op

```
createPre: ->Bool
createPost: C ->Bool
pushPre: ->Bool
pushPost: C, E, C ->Bool
popPre: C, C ->Bool
popPost: C, C ->Bool
topPre: C, E ->Bool
topPre: C, E ->Bool
..
```

```
% Q2.lp
%% Using OrderedContainer
%%% thaw OrderedContainer_Axioms
%% signature Q2
set name Q2
declare var
e: E
q1: C
q2: C
...
declare op
addPre: C, E, C ->Bool
```

add $Post: C, E, C \rightarrow Bool$...

assert

addPre(q1, e, q2) = (size(q1) < 50); addPost(q1, e, q2) = (size(q2) = size(q1) + 1) ..

assert

createPre = true; createPost(s) = (s = empty); pushPre = true; pushPost(s, e, s2) = (s2 = insert(e,s)); popPre(s, s2) = (\sim (isEmpty(s))); popPost(s, s2) = (s2 = butLast(s)); topPre(s, e) = (\sim (isEmpty(s))); topPost(s, e) = (e = last(s)) ..



container variables q1 and q2, and operators addPre and addPost. The **assert** clause adds axioms to the logical system for addPre and addPost, corresponding to the **requires** and **ensures** clauses of add, respectively.

Given the names of two function specifications, their corresponding specification files, and which match definition to use, we also generate the appropriate LP input to initiate an attempt to determine the match between those two functions. For example, Figure 6 shows the LP input to prove the plug-in match of Stack *push* with Q2. The input to LP for the proof consists simply of commands to load the theories for the library and query (execute *Stack* and execute Q2), and the proof statement (prove ...).

% PlugIn-Q2-Stack.lp %% Load library and query specs execute Stack execute Q2

%% Plug-in Match: (Qpre => Spre) /\ (Spost => Qpost) **prove** (addPre(s, e, s2) => pushPre) /\ (pushPost(s, e, s2) => addPost(s, e, s2))

Figure 6: LP input for plug-in match of *Stack.push* with Q2

We could alternatively have chosen to generate the LP axioms on a per-query basis rather than generating axioms for each .sig file (i.e., given a particular pair of functions, generate only the necessary axioms for that particular pair). However, we assume that generating an .lp file from a .sig file will happen only once and that there may be several queries on a library specification or several match definitions for a particular query. This approach enables us to consider module-level matches as well.

Since LP is designed as a proof assistant, rather than an automatic theorem prover, some of the proofs require user assistance. Each of the 40 entries in Table 3 corresponds to a match that we have used LP to prove. In characterizing how much assistance the proofs require, we consider only the *primary matches* (the 11 entries in the table that are not in parentheses), since proofs for all others follow automatically from an entry to the left in the same row. Table 4 summarizes the level of user assistance required for the primary matches. *None* means the proof went through with no user assistance, *guidance* means that the proof required user input to apply the appropriate proof strategies, and *lemma* means that the user had to prove additional lemmas to complete the proof.

Query	Library	Match	User Assistance
Q1	Queue.create	Exact Pre/Post	lemma
Q1	${\it Stack.create}$	Exact Pre/Post	lemma
Q2	Queue.enq	Plug-in	none
Q2	${\it Stack.push}$	Plug-in	none
Q3	${\it Stack.top}$	Specialized	none
Q3	${\it Stack.top}$	Plug-in Post	none
Q4	Queue.rest	Guarded Plug-in	lemma
Q4	$\operatorname{Stack.pop}$	Guarded Plug-in	guidance
Q5	Queue.rest	Guarded Post	lemma
Q5	$\operatorname{Stack.pop}$	Guarded Post	guidance
Q6	${\it Stack.top}$	Guarded Plug-in	guidance

Table 4: Level of user assistance required for LP proofs of queries

Four of the proofs needed no assistance from the user: plug-in match of Stack.push and Queue.enq with Q2, and plug-in post and specialized matches of Stack.top with Q3. Plug-in match of

% exec M-Guard-Q6-Stack %% Load library and query specs execute Stack execute Q6

```
%% Guarded Plug-in Match: (Qpre => Spre) /\ ((Spre /\ Spost) => Qpost)
prove (qTopPre(c, e) => topPre(c, e)) /\ ((topPre(c, e) /\ topPost(c, e)) => qTopPost(c, e))
% Additional user input
resume by induction
<>> basis subgoal
[] basis subgoal
<>> induction subgoal
c> induction subgoal
[] specialization subgoal
[] induction subgoal
[] induction subgoal
[] conjecture
%% End of input from file 'Guard-Q6-Stack.lp'.
```

Figure 7: Proof script of generalized match of Stack.pop with Q6

Stack.push with Q2 is the example shown in Figure 6; executing the statements in Figure 6 results in the response from LP that the match conjecture was proved using the default proof methods; no user assistance was required.

Guarded plug-in match of *Stack.pop* with Q6 is an example of a match that requires some user assistance to LP. The user must tell the prover to use induction in the proof, and then how to instantiate the existential variables. Figure 7 shows an LP-annotated script for this proof. The lines with boldface are user input; <> and [] are proof notes from LP; and % is the comment character. The line [] conjecture indicates that LP completed the proof. We classify the user assistance for this proof as simply guidance – telling LP what proof strategy to use next in cases where the default strategies do not complete the proof. A total of three proofs require guidance: guarded plug-in matches of *Stack.top* with Q6 and of *Stack.pop* with Q4, and guarded post match of *Stack.pop* with Q5.

The remainder of the proofs (exact pre/post match of *Queue.create* and *Stack.create* with Q1, guarded post match of *Queue.rest* with Q4, and guarded post match of *Queue.rest* with Q5) required not only guidance but also additional *lemmas* in order to prove the match. In all four cases, one of the additional lemmas is \sim (insert(e,q) = empty) (something that might reasonably be included in a more complete theory of containers). The proofs for *Queue.rest* with Q4 and Q5 additionally need the lemma size(butFirst(insert(e,q))) = size(q), which falls out directly from the axioms for *Stack* but not *Queue*. The proofs for Q1 need additional lemmas about the sizes of containers. Figure 8 shows an LP-annotated script for the proof of guarded post match of *Queue.rest* with Q5.

```
% exec M-GuardPost-Q5-Queue
%% Load library and query specs
execute Queue
execute Q5
set name Lemma
prove \sim(insert(e,q) = empty) by contradiction
    <> contradiction subgoal
    critical-pair *Hyp with OrderedContainer
    [] contradiction subgoal
  [] conjecture
prove size(butFirst(insert(e,q))) = size(q) by induction on q
    <> basis subgoal
    [] basis subgoal
    <> induction subgoal
    [] induction subgoal
  [] conjecture
set name Query
prove restPre(q, q2) /\ restPost(q, q2) => remainderPost(q, q2)
  resume by induction on q
    <> basis subgoal
    [] basis subgoal
    <> induction subgoal
    [] induction subgoal
  [] conjecture
  %% End of input from file 'M-GuardPost-Q5-Queue.lp'.
```

Figure 8: Proof script of guarded post match of Queue.rest with Q5

6. Applications

As we mentioned in Section 1, any problem that involves comparing the behavior of two software components is a potential candidate for specification matching. In particular, we focus on problems that center around substituting one component for another. In this section, we examine two such problems: retrieval for reuse and subtyping of object-oriented types.

6.1. Retrieval for Reuse

If we have a library of components with specifications, we can use specification matching to retrieve components from the library. Formally, we define the retrieval problem as follows:

Definition 13 (Retrieval)

Retrieve: Query Specification, Match Predicate, Component Library \rightarrow Set of Components Retrieve $(Q, match_{spec}, L) = \{C \in L : match_{spec}(C, Q)\}$

Given a query specification Q, a specification match predicate $match_{spec}$, and a library of component specifications L, Retrieve returns the set of components in L that match with Q under the match predicate $match_{spec}$. Note that the components can be either functions or modules, provided that $match_{spec}$ is instantiated with the appropriate match. Parameterizing the definition by $match_{spec}$ also gives the user the flexibility to choose the degree of relaxation in the specification match.

Using specification match as part of the retrieval process (or separately on a given pair of components) gives us assurances about how appropriate a component is for reuse. At the function level especially, the various specification matches give us various assurances about the behavior of a component we would like to use. We treat Q as the "standard" we expect a component to meet, and S as the library component we would like to reuse. If the exact pre/post match holds on S and Q, we know that S and Q are behaviorally equivalent under all conditions; using S for Q should be transparent. If the plug-in or guarded plug-in match holds, we know that S can be substituted for Q and the behavior specified by Q will still hold, although we are not guaranteed the same behavior when Q_{pre} is false. If the guarded post match holds, we know that the specified behavior holds when S_{pre} is satisfied. Depending on the context, we may be able to ensure that S_{pre} holds and hence guarantee the behavior specified by Q.

For example, suppose that we are implementing a file cache manager. Among many other things, we will need a function to replace a file in the cache with a newly-fetched file when the cache is full. We want to know whether there are functions in the library to do this. Given that library functions have specifications associated with them, we can use specification matching to retrieve the functions we want. If we use a match definition like guarded plug-in match, we can use a fairly weak specification like Q7 as our query:

```
signature Query = sig (Q7)

(*+ using OrderedContainer +*)

type \alpha fscache based on OrderedContainer.E OrderedContainer.C +*)

val qReplace : \alpha fscache * \alpha \rightarrow unit

(*+ qReplace (cache, file)

requires size (cache, file)

modifies cache

ensures isIn(file, cache') and (size(cache') = size(cache)) +*)

end

(Q7)
```

Q7 specifies a property that would hold for a destructive replacement function, namely that the size of the cache remains the same and that the new file is in the cache in the final state. The query function takes as input a file system cache (of type α *fscache*) and a file (of type α). The **requires** clause indicates that the cache must be a particular size (i.e., we are assuming that we are operating on a full cache). The **modifies** clause indicates that the value of *cache* may be changed

```
signature Component1 = sig
    (*+ using OrderedContainer +*)
    type \alpha fscache based on OrderedContainer. E OrderedContainer. C +*)
    val replaceFirst : \alpha fscache * \alpha \rightarrow unit
    (*+ replaceFirst (cache, file))
      requires not(isEmpty(cache))
      modifies cache
      ensures cache' = insert(file, butFirst(cache)) +*)
end
signature Component2 = sig
    (*+ using OrderedContainer +*)
    type \alpha fscache based on OrderedContainer.E OrderedContainer.C +*)
    val replaceMax : \alpha fscache * \alpha \rightarrow unit
    (*+ replaceMax (cache, file))
      requires not(isEmpty(cache))
      modifies cache
      ensures cache' = insert(file, delete(max(cache), cache)) +*)
end
```

Figure 9: Two library file replacement functions

by the function. In the **ensures** clauses, we use cache' to stand for the value of the cache in the final state and the unprimed cache to refer to the value in the initial state.

Suppose that the two functions listed in Figure 9 are in the library. Both require that the cache be non-empty and replace a current element of the cache with the new file. The *replaceFirst* function in *Component1* uses a FIFO replacement strategy: the first file inserted is the one replaced (e.g., the file that has been in the cache the longest). The *replaceMax* function in *Component2* uses a priority-based replacement strategy: it replaces the maximum element in the cache, for some (unspecified) total ordering on the elements of the cache. This ordering could be based on the time since the file was last referenced (i.e., an LRU replacement strategy) or on the priority of the elements in the cache (e.g., hoard priorities).

Using guarded plug-in match, retrieval using the query Q7 returns both of the library functions in Figure 9 since both replacement strategies guarantee the properties specified in Q7's postcondition. Proofs of guarded plug-in match of both *replaceFirst* with Q7 and *replaceMax* with Q7are shown in Appendix B.

Thus, we could use both of these functions to experiment with the effects of a particular replacement strategy on the performance of our cache manager. We could also use a more specific query (e.g., the same as one of the library components) to distinguish between the two library components.

This example also illustrates the importance of the pre-condition guard in guarded plug-in match. If we used plug-in match rather than guarded plug-in, we would not retrieve either function,

since it is necessary to exclude the case of an empty cache when trying to prove that the size of cache and cache' are equal.

6.2. Subtyping

A second application of specification matching is determining when one object is a subtype of another. In object-oriented programming languages, an *object type*² defines a collection of *objects*, which consist of *data* (state) and *methods* that act on the data [Car89, Ame91, Mey88]. Intuitively, a type σ is a subtype of another type τ if an object of type σ can be substituted for an object of type τ . Precise definitions of subtyping vary in the strictness of this notion of substitutability from simply requiring the methods' signatures to match (*signature subtyping*) to requiring a correspondence between the methods' dynamic semantics (*behavioral subtyping*).

In order to relate subtyping to signature and specification matching, we must first convert object types to our context. We base our definition of an object type on that of Liskov and Wing [LW94] but differ from their definition in that we do not include invariants or constraints. We restrict our focus here to relating methods, which is only one aspect of their subtyping relation. We model an object type as a module interface, with a type declaration for the object type (a description of the object type's value space), a global variable of the object type to hold the current state of the object (an element of the value space), and a function signature (and specification) for each method.

Let T represent the module interface of the supertype and S the module interface of the subtype. Subtyping requires a correspondence between each method in T and a method in S but allows additional methods in S. The correspondence between methods varies among the subtype definitions but is always a function match definition. There is also a correspondence between type declarations. These are exactly the correspondences captured by the module match definition (Definition 12). Thus, we define subtyping in terms of module match using the following general form:

Definition 14 (Generic Subtype)

 $Subtype(S,T) = M\text{-}match(S, T, match_{method})$

S is a subtype of T if their modules match. The particular notion of subtyping depends on $match_{method}$, the match used at the method (function) level. We discuss other possible instantiations of $match_{method}$ and the more general relation between both signature and behavioral subtyping to signature and specification matching in more detail elsewhere [Zar96]. In the remainder of this section, we relate behavioral subtyping to specification matching and illustrate how to use specification matching to show that one object is a behavioral subtype of another with an example.

Figure 10 shows the module specifications for two objects (example similar to that in Liskov and Wing [LW94]). The first is BagObj, a mutable bag object with global variable b and methods *put*, *get*, and *card*. The second specification is of a stack object. *StackObj* is based on the same trait as bag, but has a stricter specification for the method that removes an object (*pop_top*) and

²These are usually simply called "types", but we need to distinguish types of objects from types in signatures.

```
signature BagObj = sig
                                                           signature StackObj = sig
    (*+ using OrderedContainer +*)
                                                               (*+ using OrderedContainer +*)
    type \alpha t (*+ based on
                                                               type \alpha t (*+ based on
      OrderedContainer. E OrderedContainer. C +*)
                                                                 OrderedContainer.E OrderedContainer.C +*)
    val b : \alpha t
                                                               val s : \alpha t
    val put: \alpha \rightarrow unit
                                                               val push : \alpha \rightarrow unit
    (*+put(e))
                                                               (*+ push (e))
      modifies b
                                                                 modifies s
      ensures b' = insert(e, b) + *)
                                                                 ensures s' = insert(e, s) + *)
    val qet: unit \to \alpha
                                                               val pop\_top : unit \rightarrow \alpha
                                                               (*+ pop\_top ()) = e
    (*+qet()) = e
      requires not(isEmpty(b))
                                                                 requires not(isEmpty(s))
      modifies b
                                                                 modifies s
      ensures (b' = delete(e, b)) and
                                                                 ensures (s' = butLast(s)) and
                (isIn(e,b)) + *)
                                                                            (e = last(s)) + *)
    val card : unit \rightarrow int
                                                               val swap\_top : \alpha \rightarrow unit
    (*+ card () = n
                                                               (*+ swap\_top (e))
      ensures n = size(b) + *
                                                                 requires not(isEmpty(s))
 end
                                                                 modifies s
                                                                 ensures s' = insert(e, butLast(s)) + *)
                                                               val height : unit \rightarrow int
                                                               (*+height()) = i
                                                                  ensures i = size(s) + *
                                                             \mathbf{end}
```

Figure 10: Larch/ML specifications of bag and stack object types

an additional method, *swap_top*. In keeping with the Liskov and Wing approach, we assume that create methods are defined elsewhere. Appendix 1 lists the *OrderedContainer* trait on which both specifications are based.

The StackObj specification differs in several ways from the Stack specification in Figure 1 (pg. 5). First, in StackObj, stacks are mutable, whereas in Stack they are not. Because the Stack specification in Section 2 specifies the behavior of a typical implementation in a functional language, its stacks are immutable. Here, however, we wish to model the specification of a stack in the object-oriented paradigm, and hence these stacks are mutable. Second, Stack has separate functions for *pop* and *top* while StackObj combines these in *pop_top*. Again, this is mainly a by-product of the difference between a functional implementation and an object-oriented one. Third, each specification has additional functions that the other does not.

We now consider how to define the behavioral subtype relation between two objects (modules). Behavioral subtyping attempts to capture the notion that anywhere in a program that an object of type T is used, we should be able to substitute an object of type S, where S is a subtype of T, and still have the same observable behavior of the program.

There are a number of definitions of behavioral subtyping that attempt to capture this substitutability property [DL96, LW94, DL92, Ame91, LW90, Lea89, Mey88]. There are subtle differences between all these subtype definitions, but common to all is the use of pre-/post-condition specifications both to describe the behavior of types and to determine whether one type is a subtype of another. Let m_T be a method of supertype T, and m_S be the corresponding method of subtype S.

Behavioral subtyping requires that each method in the supertype T have a corresponding method in the subtype S, but there may be additional methods in S. We use the following rules for behavioral subtyping:

- Pre-condition rule. $m_T.pre \Rightarrow m_S.pre$
- Post-condition rule. $(m_S.pre \land m_S.post) \Rightarrow m_T.post$

This is the same as our guarded plug-in match, and is used for the same reason: to show substitutability, making assumptions about the pre-condition when necessary. Thus, we define behavioral subtyping by instantiating $match_{method}$ in the generic subtype definition (Definition 14) with guarded plug-in match (Definition 7, pg. 11). We assume that the signatures match.

Definition 15 (Behavioral Subtype)

 $Subtype_{behav}(S,T) = M\text{-}match(S_{spec}, T_{spec}, match_{guarded-plug-in})$

We can model other versions of behavioral subtyping by substituting other function specification definitions for $match_{method}$. For example, substituting plug-in match for $match_{method}$ yields America's subtype definition [Ame91], which is also the methods rule in Liskov and Wing's subtype definition [LW94]. Substituting a conjunction of generalized match with the pre-condition rule from plug-in match (i.e., $match_{method} = (m_T.pre \Rightarrow m_S.pre) \land (m_S.pred \Rightarrow m_T.pred)$) yields Dhara and Leaven's method rule [DL96].

Consider the StackObj and BagObj specifications in Figure 10. If we expect a bag object, we will not be surprised by the behavior of a stack object (i.e., we should be able to substitute a stack for a bag). Stack *push* adds an element to a container, just as bag *put* does, and stack *height* returns the size of a container, just as bag *card* does. Bag *get* is non-deterministic: it deletes and returns an element in a container. Stack *pop_top* is just more restrictive about which element it deletes. In contrast, if we expect a stack object, we may be surprised by a bag object when we remove an element, since the bag *get* method may remove an element other that the top. Thus, intuitively we would expect stack to be a subtype of bag but not vice versa. We would like to show that *StackObj* is a behavioral subtype of *BagObj* according to Definition 15. As the objects are specified, we would not be able to show the subtype relation if we used plug-in match as the method match, because we cannot prove $match_{plug-in}(pop_top, get)$ (since we cannot reason about the case where the stack or bag is empty). However, we can show that *StackObj* is a behavioral subtype of *BagObj*, since our behavior subtype definition uses guarded plug-in match, which specifically allows us to exclude the case where the stack or bag is empty.

To show $Subtype_{behav}(StackObj, BagObj)$ (or equivalently, M-match $(StackObj_{spec}, BagObj_{spec}, match_{guarded-plug-in})$), we must define the mappings U_F and U_{TC} to satisfy the three requirements

of module match in Definition 12. There is only one user-defined type in both StackObj and BagObj, and it is the same (i.e., $UserOp(\Sigma_{BagT}) = UserOp(\Sigma_{StackT}) = t$). So U_{TC} is the identity function $(U_{TC}(t) = t)$. We define U_F as follows: $U_F(put) = push$, $U_F(get) = pop_top$, and $U_F(card) = height$. U_{TC} and U_F satisfy the three requirements of module match:

- (1) U_{TC} and U_F are both one-to-one total functions. (U_F is not onto, but does not need to be.)
- (2) $match_E(\alpha t, \alpha t)$
- (3) matchguarded-plug-in (push, put) matchguarded-plug-in (pop_top, get) matchguarded-plug-in (height, card)

We translated our specifications of StackObj and BagObj into LP input and were able to prove the guarded plug-in matches with very little user guidance. Appendix C shows the LP proof script of guarded plug-in match between each pair of methods. The proofs for $match_{guarded-plug-in}(push, put)$ and $match_{guarded-plug-in}(height, card)$ are trivial, since the specifications are identical modulo variable names. The proof for $match_{guarded-plug-in}(pop_top, get)$ requires an additional lemma and some guidance.

Thus, not only have we shown how subtyping fits into our framework of specification matching, but we can also use our specification matching tools to automate checking our subtype relation. Other subtype definitions (e.g., Liskov and Wing [LW94]) include additional global information, such as invariants and constraints, which we do not model. It should be possible, however, to add this in our framework by extending Σ_T to include constraint specifications in addition to user-defined type declarations.

7. Related Work

Other work on specification matching has focused on using one or two particular match definitions for retrieval of software components (usually functions). Rollins and Wing proposed the idea of function specification matching and implemented a prototype system in λ Prolog using plug-in match [RW91]. λ Prolog does not use equational reasoning, and so the search may miss some functions that match a query but require the use of equational reasoning to determine that they match. The VCR retrieval system [FKS94] uses plug-in match with VDM as the specification language. The focus of this work is on efficiency of proving match; the tool performs a series of filtering steps before doing all-out match. Penix and Alexander [PA95] use theorem proving to translate automatically specifications into domain-specific feature sets (sets of attribute-value pairs), which they then use to do a more efficient retrieval. Such an approach depends on formulating the feature sets for each domain, however. Perry's Inscape system [Per89] is a specification-based software development environment. Its Inquire tool [PP93] provides predicate-based retrieval in Inscape. Match can be either exact pre/post or a form of generalized match. The prototype system has a simplified and hence fairly limited inference mechanism. In Inscape, the user must provide specifications for each component anyway, so the query for a retrieval will already be written. Jeng and Cheng [JC92] use order-sorted predicate logic specifications. They define two matches, both of which are instances of our generalized function match, but with the additional property that they generate a series of substitutions to apply to the library component to reuse in the desired context. Mili, Mili and Mittermeir [MMM94] define a specification as a binary relation. A specification S refines another specification Q if S has information about more inputs and assigns fewer images to each argument. This is like plug-in match except that the match is in terms of relations rather than predicates.

The PARIS system [KRT87] maintains a library of partially interpreted *schemas*. Each schema includes a specification of assertions about the input and results of the schema and about how the abstract parts of the schema can be instantiated. Matching corresponds to determining whether a partial library schema could be instantiated to satisfy a query. The system does some reasoning about the schemas but with a limited logic. Katoh, Yoshida and Sugimoto [KYS86] use "ordered linear resolution" to match English-like specifications that have been translated into first-order predicate logic formulas. They allow some relaxations but check only for equivalence and do not verify that the subroutines match.

To summarize, our work on specification matching is more general than the above in three ways: We handle not just function match, but module match; we have a framework, which is extremely modular (e.g., function match is a parameter to module match; specification match is one conjunct of component match), within which we can express each of the specific matches "hardwired" in the definitions used by others; and we have a flexible prototype tool that lets us easily experiment with all the different matches. Finally, we are not wedded to just the software retrieval application; we also apply specification match to other application areas.

Signature matching is a very restricted form of specification matching. Most work in this area has focused on using the expressiveness and theoretical properties of type systems to define various forms of relaxed matches [ZW95, DC92, Rit92, RT89, SC94]. Chen, Hennicker, and Jarke [CHJ93] describe a framework for both signature and specification matching, but have only implemented signature matching. Wileden et. al. survey *specification-level interoperability* [WWRT91]. Most work thus far has focused on signature-based interoperability, and how to convert types in a heterogeneous environment [Kon93, YS94, Tha94].

Less closely related work, but relevant to our context of software library retrieval, divides into three categories. Text-based information retrieval [FN87, AS87, PD89, MBK91] and AI-based semantic net classifications [OHPDB92, FHR91] have the advantage that many efficient tools are available to do the search and match in these structures. The disadvantage is that a component's behavior is described informally. A third class of retrievals [PP94, CMR92] allows queries over a representation of the component's actual code, e.g., abstract syntax trees. Such queries are useful mainly for determining structural characteristics of a component, e.g., nested loops or circular dependencies.

8. Summary and Future Work

Our work described in this paper makes three specific contributions with respect to specification matching: foundational definitions, a prototype tool, and descriptions of applications. By providing precise definitions, we lay the groundwork for understanding when two different software components are related, in particular when their specifications match. Though we consider in detail functions and modules, exact and relaxed match, and formal pre-/post-condition specifications,

the general idea behind specification matching is to exploit as much information associated with the description of software components as possible. By building a working specification match engine, we demonstrated the feasibility of our ideas. With this tool, we can explore the pragmatic implications of our definitions and apply specification matching to various applications. Though our notion of specification match was originally motivated by the software library retrieval application, it is more generally applicable to other areas of software engineering, for example, determining subtyping in designing class hierarchies, or showing that one component may be substituted for another when upgrading a system.

The heart of an interoperability problem is that the interfaces of two or more systems do not match [VLP94]. Thus our work makes a step in the direction of detecting an interoperability problem based on a system's interface that specifies its input-output (black-box) functional behavior. However, even if two components' specifications match according to our notion of interface specification, they may still fail to interoperate. One reason is that they may differ in the way they choose to communicate with their environment. One way to extend our work is to add more information to interface specifications to enable detection of other ways components interact with each other. Toward this goal, Allen and Garlan [AG94] use a subset of CSP to specify "protocols" as a way to capture the way a component communicates with its environment and to determine when components interoperate smoothly with each other based on these protocol specifications. Hence, a more complete interface would include protocol specifications as well as our kind of functional specification; our notion of specification match could similarly be extended to include a notion of protocol match. We deliberately set up our framework to allow different notions of specification and different notions of specification match, depending on one's personal definition of specification.

Finally, we can invert the notion of specification match: Determining that two components do not match is determining that they mismatch. Garlan, Allen, and Ockerbloom [GAO95] take a step toward understanding this notion of mismatch at a system's architectural level. Hence, a promising direction of future work is to extend our formal framework from the module level to the architectural level by modeling the various kinds of *architectural mismatch* they describe informally.

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A The OrderedContainer trait

OrderedContainer (E , C) : trait

asserts

```
C generated by empty, insert
C partitioned by count
\forall e, e1 : E, c : C
    last(insert(e, c)) == e
    butLast(insert(e, c)) == c
    first(insert(e, c)) == \mathbf{if} \ c = empty \ \mathbf{then} \ e \ \mathbf{else} \ first(c)
    butFirst(insert(e, c)) == \mathbf{if} \ c = empty \ \mathbf{then} \ empty \ \mathbf{else} \ insert(e, butFirst(c))
    max(insert(e, c)) == \mathbf{if} \ c = empty \ \mathbf{then} \ e
                             else if e > max(c) then e else max(c)
    butMax(insert(e, c)) == delete(max(c), c)
    isEmpty(empty)
    \neg isEmpty(insert(e, c))
    \neg isIn(e, empty)
    isIn(e, insert(e1, c)) == (e = e1) \lor (isIn(e, c))
    size(empty) == 0
    size(insert(e, c)) = size(c) + 1
    size(delete(e, c)) == if isIn(e, c) then size(c) - 1 else size(c)
    count(e, empty) == 0
    count(e, insert(e_1, c)) == count(e, c) + (if e = e_1then 1 else 0)
    count(e, delete(e1, c)) == if e = e1 then max(0, count(e, c) - 1) else count(e, c)
```

B Retrieval example proofs

%% Guarded plug-in match of replaceFirst with Q7

execute replace-fifo.lp execute query7.lp

%% Guarded Plug-in match - pre-condition **prove** (qReplacePre(cache, newobj) => replaceFirstPre(cache, newobj)) **resume by induction on** cache

%% Additional Lemmas **set name** Lemma **prove** ~(insert(newobj,cache) = empty) **by contradiction critical-pair** *Hyp **with** Container

prove size(butFirst(insert(e,cache))) = size(cache) by induction on cache

%% Guarded Plug-in match - post-condition set name Query prove (replaceFirstPre(cache, newobj) /\ replaceFirstPost(cache, cache', newobj)) => qReplacePost(cache, cache', newobj) resume by induction on cache

%% Full Guarded Plug-in match

```
prove (qReplacePre(cache, newobj) => replaceFirstPre(cache, newobj)) /\
    ((replaceFirstPre(cache, newobj) /\ replaceFirstPost(cache, cache', newobj)) =>
    qReplacePost(cache, cache', newobj))
```

 \mathbf{qed}

%% Guarded plug-in match of replaceMax with Q7

```
execute replace-priority.lp
execute query7.lp
```

```
%% Guarded Plug-in match - pre-condition

prove (qReplacePre(cache, newobj) => replaceMaxPre(cache, newobj))

resume by induction on cache
```

%% Additional Lemmas **set name** Lemma

```
prove ~(c=empty) => ~isEmpty(c)
resume by induction on c
```

```
prove ~(isEmpty(c)) => isIn(max(c),c)
resume by induction on c
resume by case cc = empty
resume by case max(cc) < e
instantiate c by cc in Lemma.1</pre>
```

prove ~(isEmpty(c)) => size(insert(e, delete(max(c), c))) = size(c)
resume by =>
instantiate c by cc in Lemma.2

%% Guarded Plug-in match – post-condition

set name Query

```
prove (replaceMaxPre(cache, newobj) /\ replaceMaxPost(cache, cache', newobj)) =>
qReplacePost(cache, cache', newobj)
```

%% Full Guarded Plug-in match

prove (qReplacePre(cache, newobj) => replaceMaxPre(cache, newobj)) /\
 (replaceMaxPre(cache, newobj) /\ replaceMaxPost(cache, cache', newobj)) =>
 qReplacePost(cache, cache', newobj)

 \mathbf{qed}

C Script of proof that stack is a behavioral subtype of bag

```
execute bagobj.lp
execute stackobj.lp
% guarded-plug-in(push, put)
prove (putPre => pushPre) /\ ((pushPre /\ pushPost(b, b', e)) => putPost(b, b', e))
  [] conjecture
\% guarded-plug-in(height, card)
prove (cardPre => heightPre) /\ ((heightPre /\ heightPost(b, i)) => cardPost(b, i))
  [] conjecture
\% Additional lemma assert 0 <= count(e,s)
prove delete(e,insert(e,s)) = s
  apply OrderedContainer.2 to conjecture
  [] conjecture
% guarded-plug-in(pop, get)
prove
  (getPre(b, e) => popPre(b, e)) / \land
  ((popPre(b,e) / popPost(b, b', e)) => getPost(b, b',e))
  ..
  resume by induction on b
    <> basis subgoal
    [] basis subgoal
    <> induction subgoal
    [] induction subgoal
  [] conjecture
qed
```