Petsy: Polymorphic Enumerative Type-Guided Synthesis

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1 INTRODUCTION

Consider the task of implementing a function that has the following description: "If I give you a function, apply it to x. Otherwise, return x unchanged." We can translate this function description into a Haskell type signature as follows:

$$f : \text{Maybe } (a \rightarrow a) \rightarrow x : a \rightarrow a \tag{1}$$

where f represents a possible function (hence the Maybe type), and x is of the same type that f takes in and returns. A possible solution to this problem is:

$$\text{\textbackslash f x -> fromMaybe (\textbackslash y -> y) f x} \tag{2}$$

which either extracts the function from the Maybe and applies it to x, or applies the identity function to x if the Maybe is Nothing (which is the same as returning x unchanged). As a component-based program, (2) is idiomatic and concise and doesn't rely on pattern matching. It is potentially non-intuitive, though, and could be difficult for programmers to find on their own.

We present Petsy, a tool that allows users to provide a type signature and optional examples, and get back a code snippet that consists of a composition of Haskell library functions. This allows users to speed up their programming by using our tool to synthesize small Haskell programs instead of doing it themselves.

2 RELATED WORK

The problem we are exploring is polymorphic type-guided synthesis via enumerative search. Related problems have been explored before.

MYTH. Myth [2] already explores enumerative search for type-directed synthesis, but it does not support polymorphism or typeclasses like we'd like Petsy to.

Tygar. Tygar [1] uses Petri nets to tackle type-guided Haskell program synthesis, and is remarkable in that it also supports polymorphic types, typeclasses, and can check user-provided input-output examples. Because of its use of Petri nets, however, it has to reduce everything to first order, meaning that it can't make use of lambdas, which limits the space of programs that Tygar can pull from.

SYNQUID. Synquid [3] makes use of an enumerative search approach, lambdas, and polymorphism. Its type system, however, restricts type variables (represented here with α) from unifying with arrow types. This prevents, for example, Maybe $a \rightarrow a$ and $\alpha_1 \rightarrow \alpha_0 \rightarrow b$ from unifying, even though in theory they could if Maybe a unified with α_1, and a unfied with $\alpha_0 \rightarrow b$. This leads to some programs being unreachable and, in the context of higher-order components, limits the search space.

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3   APPROACH

3.1   Synthesis Problem

Our synthesis *problem* consists of a component library, a query type, and optional input-output examples. A *solution* to the synthesis problem is a Haskell code snippet that has the desired type and works for the optionally given examples.

3.2   Extending SYNQUID's enumeration strategy

SYNQUID also solves itsw synthesis task via top-down enumerative search. The task it solves is similar, the only difference being that the types are not just polymorphic – they are liquid (refinement) types. Among other reasons, SYNQUID's method of supporting refinements requires it to determine whether a type is a scalar without having to substitute its type variables. This is made possible by restricting type variables to not unify with arrow types. Because PETSY employs an enumerative search method instead, there is no reason to have this restriction.

Petsy is built on top of Synquid, ignoring all the refinement type logic since our synthesis task does not involve refinements. We also change the type system such that type variables are no longer restricted to unify only with scalar types – type variables can now unify with arrows. This means PETSY can synthesize a wider range of programs. One concrete example is the query $(a \rightarrow b, a) \rightarrow b$, with components [fst of type $\forall x. \forall y. (x, y) \rightarrow x$, snd of type $\forall x. \forall y. (x, y) \rightarrow y$]. The solution is fst p (snd p), which is only possible if $\forall x. \forall y. (x, y)$ in the type of the component fst, $\forall x. \forall y. (x, y) \rightarrow x$, unifies with the type of p, $(a \rightarrow b, a)$. Because the type variable x needs to unify with the arrow type $a \rightarrow b$, PETSY is able to synthesize this while SYNQUID cannot.

3.3   Memoization (caching subproblems during enumeration)

Because of its enumerative and iterative deepening qualities, PETSY generates many repeated subproblems over the course of the search, wasting a lot of time redoing searches it has already done. This makes memoization crucial to practical top-down enumeration, which MYTH [2] is able to solve in a first-order setting.

In our polymorphic context, however, memoization is non-trivial, as goal types can now contain free type variables.

Memoization is mechanically difficult to deal with in a polymorphic setting, because we have to be careful when dealing with goals that overlap (example: $\alpha_0 \rightarrow$ Int and $\alpha_1 \rightarrow$ Int and (Int $\rightarrow$ Int) $\rightarrow$ Int). However, we discovered that the following methods resolve these problems.

3.3.1   Overlapping Goals. To resolve a space explosion issue where equivalent goals $\alpha_0 \rightarrow$ Int and $\alpha_1 \rightarrow$ Int contain the exact same programs being stored in two different locations, the cache renames all free type variables in goals – the first type variable becomes β_0, the second becomes β_1, and so on. This treats both goals as $\beta_0 \rightarrow$ Int, making syntactically different goals semantically equivalent.

3.3.2   Preserving Unification. The previous method with β's introduces a small issue in program retrieval. Consider how the program length of type $[\alpha_1] \rightarrow$ Int solves the goal $\alpha_0 \rightarrow$ Int. This unifies $[\alpha_1]$ with α_0, which is important information for SYNQUID's algorithm. With memoization, however, length gets stored in the cache for the goal $\beta_0 \rightarrow$ Int. When length is retrieved from the cache to solve $\alpha_0 \rightarrow$ Int, we lose the fact that α_0 now unifies with a list, as this information is never stored.

Instead of worrying about how to store this information, we decided to simply unify the type of length, $[\alpha_1] \rightarrow$ Int, with the goal type $\alpha_0 \rightarrow$ Int at the time of retrieval. This recovers the unification information. Obtaining the type of the retrieved program is easy when the program is a

Table 1. Tygar vs. Petsy

N	Name	Query	Tygar	Petsy
1	test	Bool -> a -> Maybe a	8.0 s	6.0 s
2	firstJust	a -> [Maybe a] -> a	18.4 s	6.5 s
3	mapEither	(a -> Either b c) -> [a] -> ([b], [c])	4.8 s	3.2 s
4	mapMaybes	(a -> Maybe b) -> [a] -> Maybe b	8.0 s	5.2 s
5	mergeEither	Either a (Either a b) -> Either a b	3.8 s	181.5 s
6	map	(a->b)->[a]->[b]	2.1 s	3.7 s
7	repl-funcs	(a->b)->Int->[a->b]	1.1 s	1.2 s
8	mbAppFirst	b -> (a -> b) -> [a] -> b	3.2 s	9.5 s
9	resolveEither	Either a b -> (a->b) -> b	4.0 s	10.3 s
10	multiApp	(a -> b -> c) -> (a -> b) -> a -> c	6.9 s	9.6 s
11	singleList	a -> [a]	7.7 s	4.4 s
12	head-last	[a] -> (a,a)	257.3 s	12.0 s
13	firstMatch	[a] -> (a -> Bool) -> a	6.0 s	6.9 s
14	rights	[Either a b] -> Either a [b]	1.9 s	2.6 s
15	firstKey	[(a,b)] -> a	1.5 s	3.4 s
16	firstRight	[Either a b] -> Either a b	4.4 s	9.6 s
17	zipWithResult	(a->b)->[a]->[(a,b)]	268.1 s	10.8 s
18	applyNtimes	(a->a) -> a -> Int -> a	30.2 s	18.0 s
19	mbElem	Eq a => a -> [a] -> Maybe a	3.7 s	295.6 s
20	flatten	[[[a]]] -> [a]	4.7 s	1.4 s

single component. To keep in consistent across single and multiple component programs (like map length), we use *type inference* to obtain the type.

4 RESULTS

We tested our results on 20 benchmarks that we took from Tygar's [1] paper. We used the same set of 130 components in all experiments. Because Tygar's search space was most similar to ours, we chose to compare Petsy with Tygar. The results can be found in Table 1.

Analysis. Petsy did better than Tygar in 9 out of the 20 tests. While there are some tests that we do much better in – #12 and #17 – and some tests that we do much worse in – #5 and #19 – both tools perform relatively the same and are quite comparable.

These results are quite encouraging. For one, since Petsy takes advantage of lambdas and Tygar doesn't, Petsy is more expressive and therefore searches through more programs, yet is still competitive. We also have only implemented the most basic form of memoization, and plan to improve upon it to make Petsy even faster (see Future Work).

Quality of Results. For the most part, both Tygar and Petsy returned the same programs. If they didn't return the same program, the programs were equivalent, so the differences between the results of the two tools is insignificant.

5 FUTURE WORK

Our memoization tool is still very basic and we think there are multiple ways in which we can improve upon what we have:

(1) Re-organize our memo map to store programs first based on size, and then find programs based on query. This would make lookup much faster.
(2) Take advange of sub-typing in the memo keys so that the same programs aren't stored multiple times. For example, all programs in goal $Int \rightarrow Int$ should be in goal $\alpha_0 \rightarrow Int$. When we lookup $\alpha_0 \rightarrow Int$, we could first look at $Int \rightarrow Int$ and then move on to other programs that are more general.

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