SEMINAR REPORT
Seminar: Programming Languages in Winter term 2024/2025

Rheinland-Pfälzische Technische Universität Kaiserslautern Landau

# Liquid Haskell

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*This report gives a brief overview of LiquidHaskell, a tool that extends Haskell with refinement types. Refinement types are types that extends expressiveness of Haskell types systems by providing predicates that can verify invarients of the program. This report explains briefly how SMT solvers leveraged by LiquidHaskell and how to use LiquidHaskell by providing some examples. Finally, we discuss the limitations of LiquidHaskell and compare it with other tools.*

## 1 Introduction

Programming verfication is an important step in software developments. It is the process of verifying that a program behaves as it expected. There has been a lot of research in this area and many tools have been developed. Type safety is one of the important features of programming languages that helps to prevent runtime errors. Despite catching many errors at compile time, type systems are not powerful enough to catch all the errors. On the other, testing is another way to verify the program, but it is not always possible to test all the possible inputs. Consider the following example:

```
average    :: [Int] -> Int
average xs = sum xs `div` length xs
```

The example above is a simple function that calculates the average of a list of integers. This can be a source of runtime error if the list is empty. While this can be caught by testing, it is not always possible to test all the possible inputs. Another way to verify the program is to use program verification tools. These tools use mathematical logic to check the program. One of such tools that is used in Haskell programming language is LiquidHaskell. LiquidHaskell (LH) extends Haskell with refinement types which are types that extend the expressiveness of Haskell. With refinement types, we can provide invariant that the program should satisfy.

In this report, after a short backgrouund on program verfication using SMT in section 2, we will explain how LH works and how it uses SMT solvers to verify the program in section 3. Then in section 4 we will provide some examples how to use LH to verify **problem name** problem. Finally in section 5 we discuss the limiations of LH and compare it with other tools.

problem name

## 2 Background

**Refinement Types** Refinement types add predicates to the types [2]. For example, consider the following type:

```haskell
{-@ incr :: Pos -> Pos @-}
incr :: Int -> Int
incr x = x + 1
```

**Predicate** Predicates are haskell expressions that evaluate to boolean.

**SMT Solvers** SMT solvers are used to check the satisfiability of the predicates.

## 2.1 SMT Solvers

SMT (Satisfiability Modulo Theories) solvers are tools that can check the satisfiability of logical formulas in a specific theory. SMT solvers extends the concept of SAT solvers by adding theories (e.g., the theory of equality, of integer numbers, of real numbers, of arrays, of lists, and so on) to the boolean logic [1]. While SAT solvers can only check the satisfiability of boolean formulas, SMT solvers can check the satisfiability of formulas that contain variables from different theories. As an example, consider the following formula:

$$\varphi = (x \vee y) \wedge (\neg x \vee z) \tag{1}$$

SAT solver can check the satisfiability of the formula $\varphi$ by checking if there is an assignment for the variables $x, y, z$. For instance, $x = true, y = false, z = true$ is an assignment that makes $\varphi$ *true*.

On the other hand, SMT solvers can check the satisfiability of formulas that contain variables that required arithmetic theory as following formula: Figure 1

$$x + y \leq 10 \quad and \quad x = y - 7 \tag{2}$$

## 2.2 Z3 SMT Solvers

Consider following example:

$$(Tie \vee Shirt) \wedge (\neg Tie \vee Shirt) \wedge (\neg Tie \vee \neg Shirt) \tag{3}$$

Formula 3 can be solved by Z3 SMT solver as following code:

```haskell
from z3 import Bools, Solver, Or, Not
Tie, Shirt = Bools('Tie Shirt')
s = Solver()
s.add(Or(Tie, Shirt),
      Or(Not(Tie), Shirt),
      Or(Not(Tie), Not(Shirt)))
print(s.check())
print(s.model())
```

The output of the code is:

```
sat
[Tie = False, Shirt = True]
```

```
Z = IntSort()
f = Function('f', Z, Z)
x, y, z = Ints('x␣y␣z')
A = Array('A', Z, Z)
fml = Implies(x + 2 == y, f(Store(A, x, 3)[y - 2]) == f(y - x + 1))
print(s.check(Not(fml)))
```

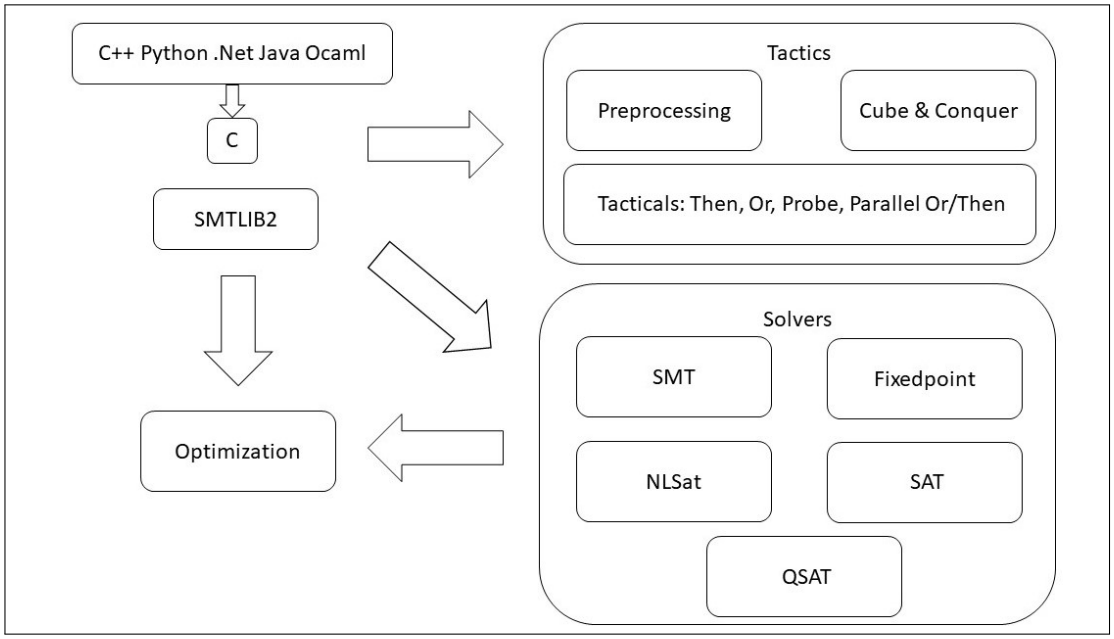


Figure 1: Overall system architecture of Z3 [4]

## 3 Working with LiquidHaskell

LH is a tool that extends Haskell with refinement types. Refinement types are types that extend the expressiveness of Haskell types systems by providing predicates that can verify invarients of the program. In this section, we will explain how to use LH and how it works. LH is available as a GHC plugin. To use LH, you need to add LH dependecy to the cabal file as following:

```
cabal-version: 1.12

name:           lh-plugin-demo
version:        0.1.0.0
...
...
  build-depends:
      liquid-prelude,
      liquid-vector,
      liquidhaskell,
```

```
      base,
      containers,
      vector
  default-language: Haskell2010
  ghc-options:  -fplugin=LiquidHaskell
```

By adding this dependency, LH can now check your program at compile time or via code linter.

## 3.1 Type Refinement

Refinement types allows to constrain the type of the variables by adding predicates to the types [2]. For example we can define natural numbers as following:

```
{-@ type Nat = {v:Int | 0 <= v} @-}
```

Now if you configure your IDE to use Haskell LSP, it will show following error if you try to assign a negative number to a variable of type Nat.

```
{-@ x :: Nat @-}
x = -1
>>> typecheck: Liquid Type Mismatch
  .
  The inferred type
    VV : {v : GHC.Types.Int | v == GHC.Num.negate (GHC.Types.I# 1)
                            && v == (-GHC.Types.I# 1)}
  .
  is not a subtype of the required type
    VV : {VV##493 : GHC.Types.Int | VV##493 >= 0}
  .
  Constraint id 2
```

The error message shows that the inferred type of the variable x is not a subtype of the required type.

Using refinement types, one can define pre-conditions and post-conditions of the functions [2]. For example, consider the following function:

```
tail :: [a] -> [a]
tail (_:xs) = xs
```

The function defined above is a partial function because it does not handle the case when the list is empty. Typicall haskell type only allows to introduce the Maybe type which postpone the handling of error other part of the program [2]. Using refinement types, we can define the type of tail function as following:

```
{-@ type NEList a = {v:[a] | 0 < len v} @-}
{-@ tail :: {v:[a] | 0 < len v} -> a @-}
```

```
tail :: [a] -> [a]
tail (x:_) = x
```

```
{-# OPTIONS_GHC -fplugin=LiquidHaskell #-}

{-@ type Pos = {v:Int | 0 < v} @-}

{-@ incr :: Pos -> Pos @-}
incr :: Int -> Int
incr x = x + 1
```

# 4 Example Application

# 5 Conclusions, Results, Discussion

## References


[1] Clark Barrett & Cesare Tinelli (2018): *Satisfiability Modulo Theories*. In Edmund M. Clarke, Thomas A. Henzinger, Helmut Veith & Roderick Bloem, editors: *Handbook of Model Checking*, Springer International Publishing, Cham, pp. 305–343, doi:10.1007/978-3-319-10575-8_11. Available at `http://link.springer.com/10.1007/978-3-319-10575-8_11`.

[2] Ranjit Jhala, Eric Seidel & Niki Vazou (2020): *Programming With Refinement Types*. Available at `https://ucsd-progsys.github.io/liquidhaskell-tutorial/`.

[3] Adithya Murali, Lucas Peña, Ranjit Jhala & P. Madhusudan (2023): *Complete First-Order Reasoning for Properties of Functional Programs*. *Proceedings of the ACM on Programming Languages* 7(OOPSLA2), pp. 1063–1092, doi:10.1145/3622835. Available at `https://dl.acm.org/doi/10.1145/3622835`.

[4] Nikolaj Bjørner, Leonardo de Moura, Lev Nachmanson & Christoph Wintersteiger: *Programming Z3*. Available at `https://z3prover.github.io/papers/programmingz3.html`.

[5] P.D. Magnus, Tim Button, Robert Trueman & Richard Zach (2023): *forall x: Calgary*. Available at `https://forallx.openlogicproject.org/html/`.

[6] Niki Vazou, Eric L. Seidel & Ranjit Jhala (2014): *LiquidHaskell: experience with refinement types in the real world*. In: *Proceedings of the 2014 ACM SIGPLAN symposium on Haskell*, Haskell '14, Association for Computing Machinery, New York, NY, USA, pp. 39–51, doi:10.1145/2633357.2633366. Available at `https://dl.acm.org/doi/10.1145/2633357.2633366`.