COMP3141

Software System Design and Implementation

Static Assurance with Types

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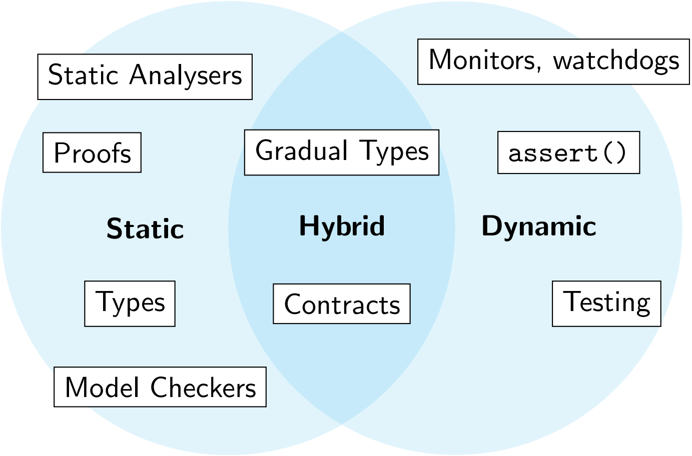
Methods of Assurance



Static means of assurance analyse a program without running it.

Static vs. Dynamic

- Static checks can be exhaustive.

Exhaustivity

An exhaustive check is a check that is able to analyse all possible executions of a program.

- **However**, some properties cannot be checked statically in general (halting problem), or are intractable to feasibly check statically (state space explosion).
- Dynamic checks cannot be exhaustive, but can be used to check some properties where static methods are unsuitable.

Compiler Integration

Most static and all dynamic methods of assurance are not integrated into the compilation process.

- You can compile and run your program even if it fails tests.
- You can change your program to diverge from your model checker model.
- Your proofs can diverge from your implementation.

Types

Because types are integrated into the compiler, they cannot diverge from the source code. This means that type signatures are a kind of machine-checked documentation for your code.

Types

Types are the most widely used kind of formal verification in programming today.

- They are checked automatically by the compiler.
- They can be extended to encompass properties and proof systems with very high expressivity (covered next week).
- They are an exhaustive analysis.

This week, we'll look at techniques to encode various correctness conditions inside Haskell's type system.

Phantom Types

Definition

A type parameter is *phantom* if it does not appear in the right hand side of the type definition.

```
newtype Size x = S Int
```

Lets examine each one of the following use cases:

- We can use this parameter to track what data invariants have been established about a value.
- We can use this parameter to track information about the representation (e.g. units of measure).
- We can use this parameter to enforce an ordering of operations performed on these values (*type state*).

Validation

```haskell
data UG -- empty type
data PG
data StudentID x = SID Int
```

We can define a smart constructor that specialises the type parameter:

```haskell
sid :: Int -> Either (StudentID UG)
                     (StudentID PG)
```

(Recalling the following definition of Either)

```haskell
data Either a b = Left a | Right b
```

And then define functions:

```haskell
enrolInCOMP3141 :: StudentID UG -> IO ()
lookupTranscript :: StudentID x -> IO String
```

Units of Measure

In 1999, software confusing units of measure (pounds and newtons) caused a mars orbiter to burn up on atmospheric entry.

```
data Kilometres
data Miles
data Value x = U Int
sydneyToMelbourne = (U 877 :: Value Kilometres)
losAngelesToSanFran = (U 383 :: Value Miles)
```

In addition to tagging values, we can also enforce constraints on units:

```
data Square a
area :: Value m -> Value m -> Value (Square m)
area (U x) (U y) = U (x * y)
```

Note the arguments to area must have the same units.

Type State

Example

A `Socket` can either be ready to recieve data, or busy. If the socket is busy, the user must first use the `wait` operation, which blocks until the socket is ready. If the socket is ready, the user can use the `send` operation to send string data, which will make the socket busy again.

```
data Busy
data Ready
newtype Socket s = Socket ...

wait :: Socket Busy -> IO (Socket Ready)

send :: Socket Ready -> String -> IO (Socket Busy)
```

What assumptions are we making here?

Linearity and Type State

The previous code assumed that we didn't re-use old Sockets:

```
send2 :: Socket Ready -> String -> String
      -> IO (Socket Busy)
send2 s x y = do s' <- send s x
                 s'' <- wait s'
                 s''' <- send s'' y
                 pure s'''
```

But we can just re-use old values to send without waiting:

```
send2' s x y = do _ <- send s x
                  s' <- send s y
                  pure s'
```

Linear type systems can solve this, but not in Haskell (yet).

Datatype Promotion

```
data UG
data PG
data StudentID x = SID Int
```

Defining empty data types for our tags is untyped. We can have `StudentID UG`, but also `StudentID String`.

Recall

Haskell types themselves have types, called kinds. Can we make the kind of our tag types more precise than $*$?

The `DataKinds` language extension lets us use data types as kinds:

```
{-# LANGUAGE DataKinds, KindSignatures #-}
data Stream = UG | PG
data StudentID (x :: Stream) = SID Int
-- rest as before
```

Motivation: Evaluation

```
data Expr = BConst Bool
          | IConst Int
          | Times Expr Expr
          | Less Expr Expr
          | And Expr Expr
          | If Expr Expr Expr
data Value = BVal Bool | IVal Int
```

Example

Define an expression evaluator:

```
eval :: Expr -> Value
```

Motivation: Partiality

Unfortunately the `eval` function is partial, undefined for input expressions that are not well-typed, like:

```
And (ICons 3) (BConst True)
```

Recall

With any partial function, we can make it total by either expanding the co-domain (e.g. with a `Maybe` type), or constraining the domain.

Can we use phantom types to constrain the domain of `eval` to only accept well-typed expressions?

Attempt: Phantom Types

Let's try adding a phantom parameter to `Expr`, and defining typed constructors with precise types:

```
data Expr t = ...
bConst :: Bool -> Expr Bool
bConst = BConst
iConst :: Int -> Expr Int
iConst = IConst
times :: Expr Int -> Expr Int -> Expr Int
times = Times
less :: Expr Int -> Expr Int -> Expr Bool
less = Less
and :: Expr Bool -> Expr Bool -> Expr Bool
and = And
if'  :: Expr Bool -> Expr a -> Expr a -> Expr a
if' = If
```

Attempt: Phantom Types

This makes invalid expressions into type errors (yay!):

```
-- Couldn't match Int and Bool
and (iCons 3) (bConst True)
```

How about our `eval` function? What should its type be now?

`eval ::` `Expr t -> t`

Bad News

Inside `eval`, the Haskell type checker cannot be sure that we used our typed constructors, so in e.g. the `IConst` case:

```
eval :: Expr t -> t
eval (IConst i) = i -- type error
```

We are unable to tell that the type `t` is definitely `Int`.

Phantom types aren't strong enough!

GADTs

Generalised Algebraic Datatypes (*GADTs*) is an extension to Haskell that, among other things, allows data types to be specified by writing the types of their constructors:

```
{-# LANGUAGE GADTs, KindSignatures #-}
-- Unary natural numbers, e.g. 3 is S (S (S Z))
data Nat = Z | S Nat
-- is the same as
data Nat :: * where
  Z :: Nat
  S :: Nat -> Nat
```

When combined with the *type indexing* trick of phantom types, this becomes very powerful!

Expressions as a GADT

```
data Expr :: * -> * where
   BConst :: Bool -> Expr Bool
   IConst :: Int -> Expr Int
   Times :: Expr Int -> Expr Int -> Expr Int
   Less :: Expr Int -> Expr Int -> Expr Bool
   And :: Expr Bool -> Expr Bool -> Expr Bool
   If   :: Expr Bool -> Expr a -> Expr a -> Expr a
```

Observation

There is now only *one* set of precisely-typed constructors.

Inside `eval` now, the Haskell type checker accepts our previously problematic case:

```
eval :: Expr t -> t
eval (IConst i) = i -- OK now
```

GHC now knows that if we have `IConst`, the type `t` must be `Int`.

Lists

We could define our own list type using GADT syntax as follows:

```
data List (a :: *) :: * where
  Nil  :: List a
  Cons :: a -> List a -> List a
```

But, if we define head (`hd`) and tail (`tl`) functions, they're partial (boo!):

```
hd (Cons x xs) = x
tl (Cons x xs) = xs
```

We will constrain the domain of these functions by tracking the length of the list on the type level.

Vectors

As before, define a natural number kind to use on the type level:

```
data Nat = Z | S Nat
```

Now our length-indexed list can be defined, called a `Vec`:

```
data Vec (a :: *) :: Nat -> * where
  Nil  :: Vec a Z
  Cons :: a -> Vec a n -> Vec a (S n)
```

Now `hd` and `tl` can be total:

```
hd :: Vec a (S n) -> a
hd (Cons x xs) = x
tl :: Vec a (S n) -> Vec a n
tl (Cons x xs) = xs
```

Vectors, continued

Our `map` for vectors is as follows:

```
mapVec :: (a -> b) -> Vec a n -> Vec b n
mapVec f Nil = Nil
mapVec f (Cons x xs) = Cons (f x) (mapVec f xs)
```

Properties

Using this type, it's impossible to write a `mapVec` function that changes the length of the vector.
Properties are verified by the compiler!

Tradeoffs

The benefits of this extra static checking are obvious, however:

- It can be difficult to convince the Haskell type checker that your code is correct, even when it is.
- Type-level encodings can make types more verbose and programs harder to understand.
- Sometimes excessively detailed types can make type-checking very slow, hindering productivity.

Pragmatism

We should use type-based encodings only when the assurance advantages outweigh the clarity disadvantages.

The typical use case for these richly-typed structures is to eliminate partial functions from our code base.

If we never use partial list functions, length-indexed vectors are not particularly useful.

Appending Vectors

Example (Problem)

```
appendV :: Vec a m -> Vec a n -> Vec a ???
```

We want to write `m + n` in the `???` above, but we do not have addition defined for kind `Nat`.

We can define a normal Haskell function easily enough:

```
plus :: Nat -> Nat -> Nat
plus Z y = y
plus (S x) y = S (plus x y)
```

This function is not applicable to type-level `Nat`s, though.
$\Rightarrow$ we need a type level function.

Type Families

Type level functions, also called *type families*, are defined in Haskell like so:

```haskell
{-# LANGUAGE TypeFamilies #-}
type family Plus (x :: Nat) (y :: Nat) :: Nat where
  Plus Z     y = y
  Plus (S x) y = S (Plus x y)
```

We can use our type family to define `appendV`:

```haskell
appendV :: Vec a m -> Vec a n -> Vec a (Plus m n)
appendV Nil         ys = ys
appendV (Cons x xs) ys = Cons x (appendV xs ys)
```

Recursion

If we had implemented `Plus` by recursing on the second argument instead of the first:

```haskell
{-# LANGUAGE TypeFamilies #-}
type family Plus' (x :: Nat) (y :: Nat) :: Nat where
  Plus' x Z     = x
  Plus' x (S y) = S (Plus' x y)
```

Then our `appendV` code would not type check.

```haskell
appendV :: Vec a m -> Vec a n -> Vec a (Plus' m n)
appendV Nil          ys = ys
appendV (Cons x xs) ys = Cons x (appendV xs ys)
```

Why?

Answer

Consider the `Nil` case. We know `m = Z`, and must show that our desired return type $\texttt{Plus}'\ \texttt{Z}\ \texttt{n}$ equals our given return type `n`, but that fact is not immediately apparent from the equations.

Type-driven development

- This lecture is only a taste of the full power of type-based specifications.
- Languages supporting dependent types (Idris, Agda) completely merge the type and value level languages, and support machine-checked proofs about programs.
- Haskell is also gaining more of these typing features all the time.

Next week: Fancy theory about types!

- Deep connections between types, logic and proof.
- Algebraic type structure for generic algorithms and refactoring.
- Using polymorphic types to infer properties for free.

Homework

1. Assignment 2 is **released**. Due on **7th August, 9 AM**.
2. The last programming exercise has been released, due next week.
3. This week's quiz is also up, due in Friday of Week 9.