Work-in-progress: Verifying the Glasgow Haskell Compiler Core language

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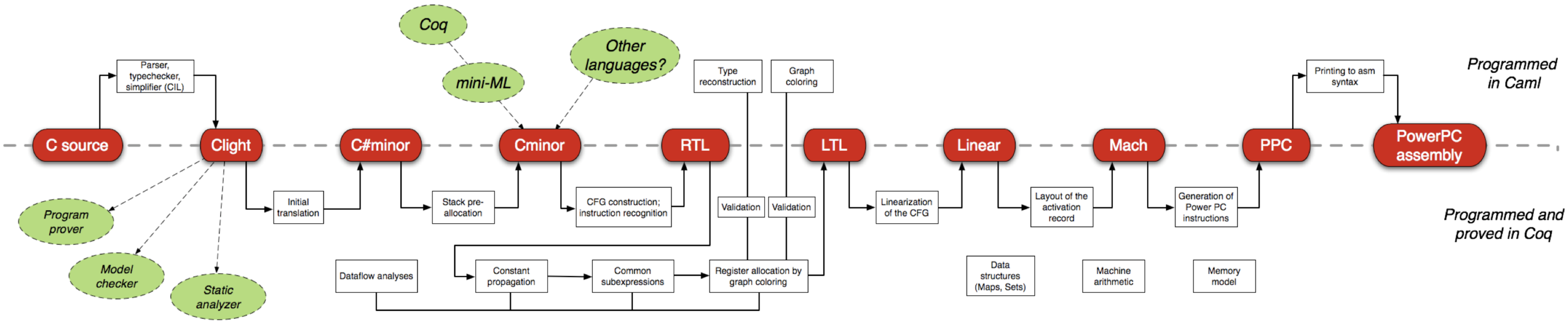
Verified compilers and security

- To be able to argue about the security of a program, we need a *specification* of the language semantics
- We also need to know that a specific compiler implements that that semantics correctly
- This talk: pragmatics of specifying and verifying a typed, higher-order functional programming language

Specified and Verified Compilation

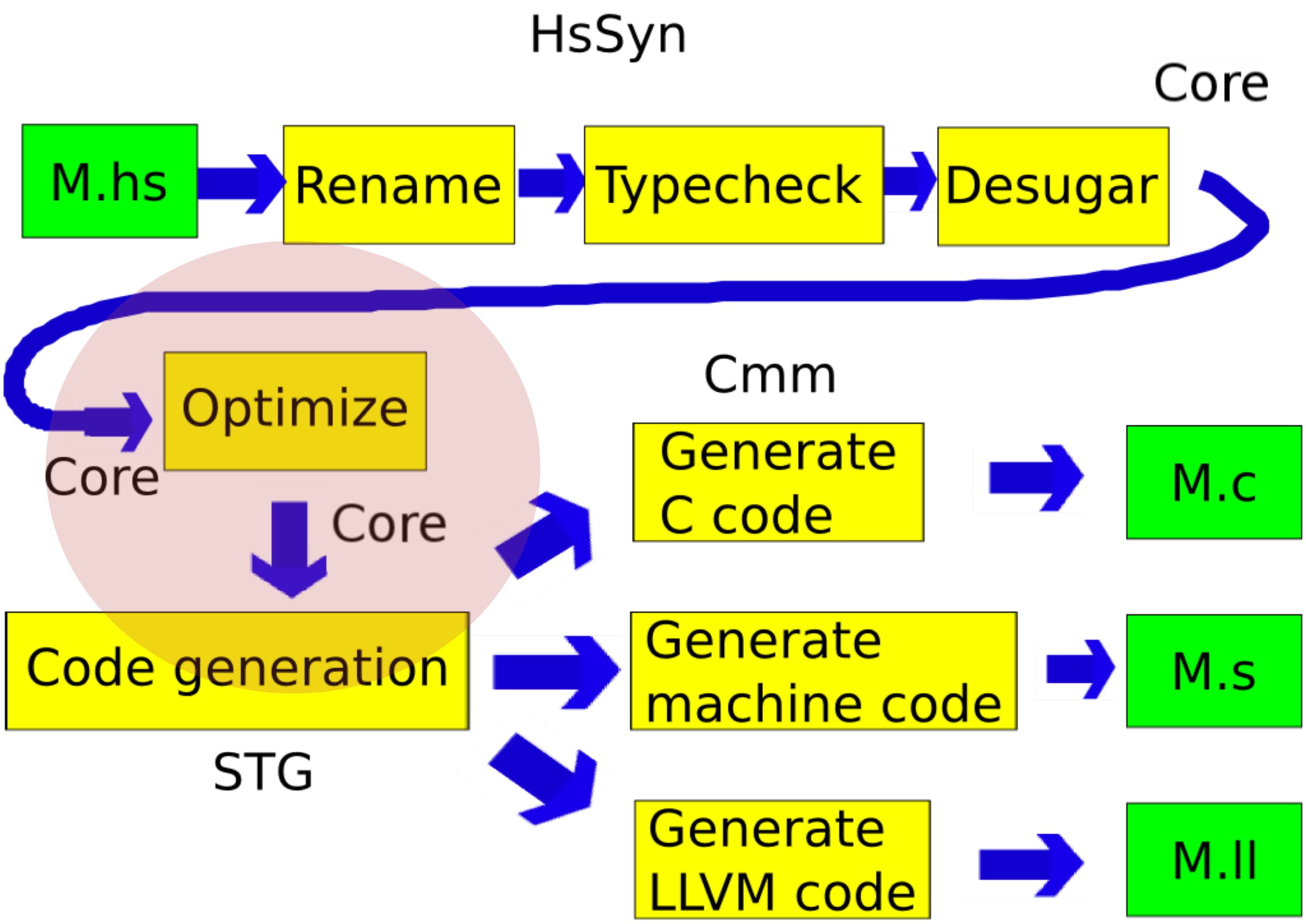
- Semantics specified using trace-based co-inductive relations
- CompCert compiler implemented as total functional program in Gallina
- Other examples: CakeML, Vellvm, etc.



What if we *already* have a compiler that we want to specify and verify?

Core Spec

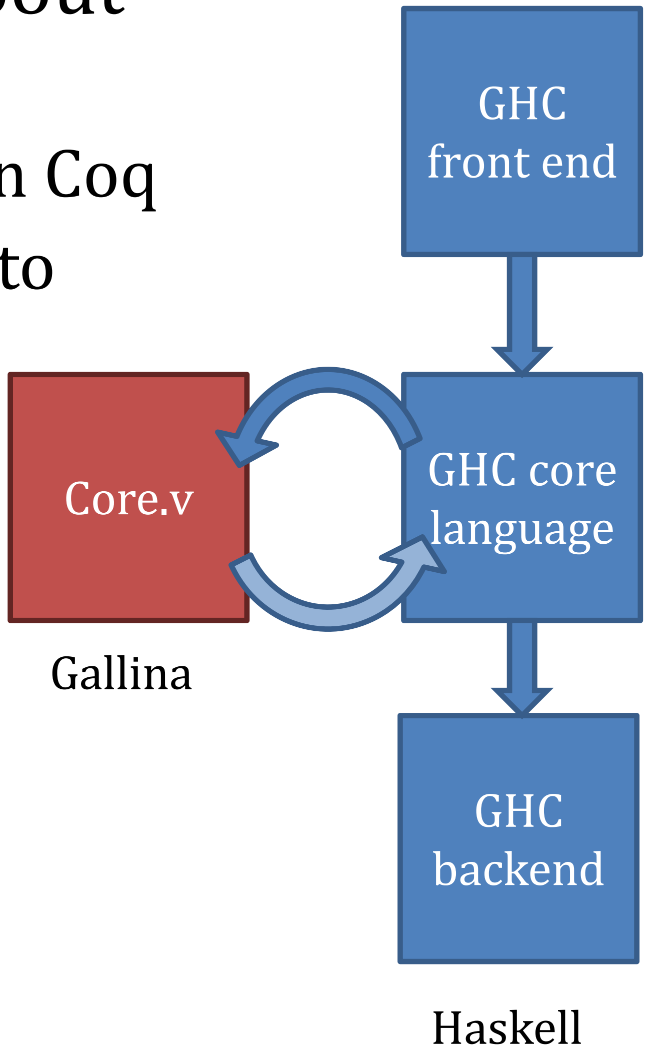
Glasgow Haskell Compiler (GHC)



GHC is a bootstrapping compiler

- Want to use Coq to reason about GHC
  - Need a semantics for Haskell in Coq
  - But that is what we are trying to build!

- "Easy" approach: shallow embedding
  - Use Gallina as a stand-in for Haskell
  - Translate Haskell functions to Gallina functions, use that as specification



Core Spec

hs-to-coq

A tool for translating Haskell code to equivalent Gallina definitions via shallow embedding [CPP' 18]

```
foldr :: (a -> b -> b) -> b -> [a] -> b
foldr k z = go
          where
            go []      = z
            go (y:ys) = y `k` go ys
```

```
Definition foldr {a} {b} : (a -> b -> b) -> b
                                    -> list a -> b :=
  fun k z =>
    let fix go arg_0__
              := match arg_0__ with
                 | nil => z
                 | cons y ys => k y (go ys)
                 end in
    go.
```

Questions about hs-to-coq approach

1. Is there enough Haskell code out there that we can translate to make this approach worthwhile?

2. Even if we can find code to translate, is the result suitable for verification?

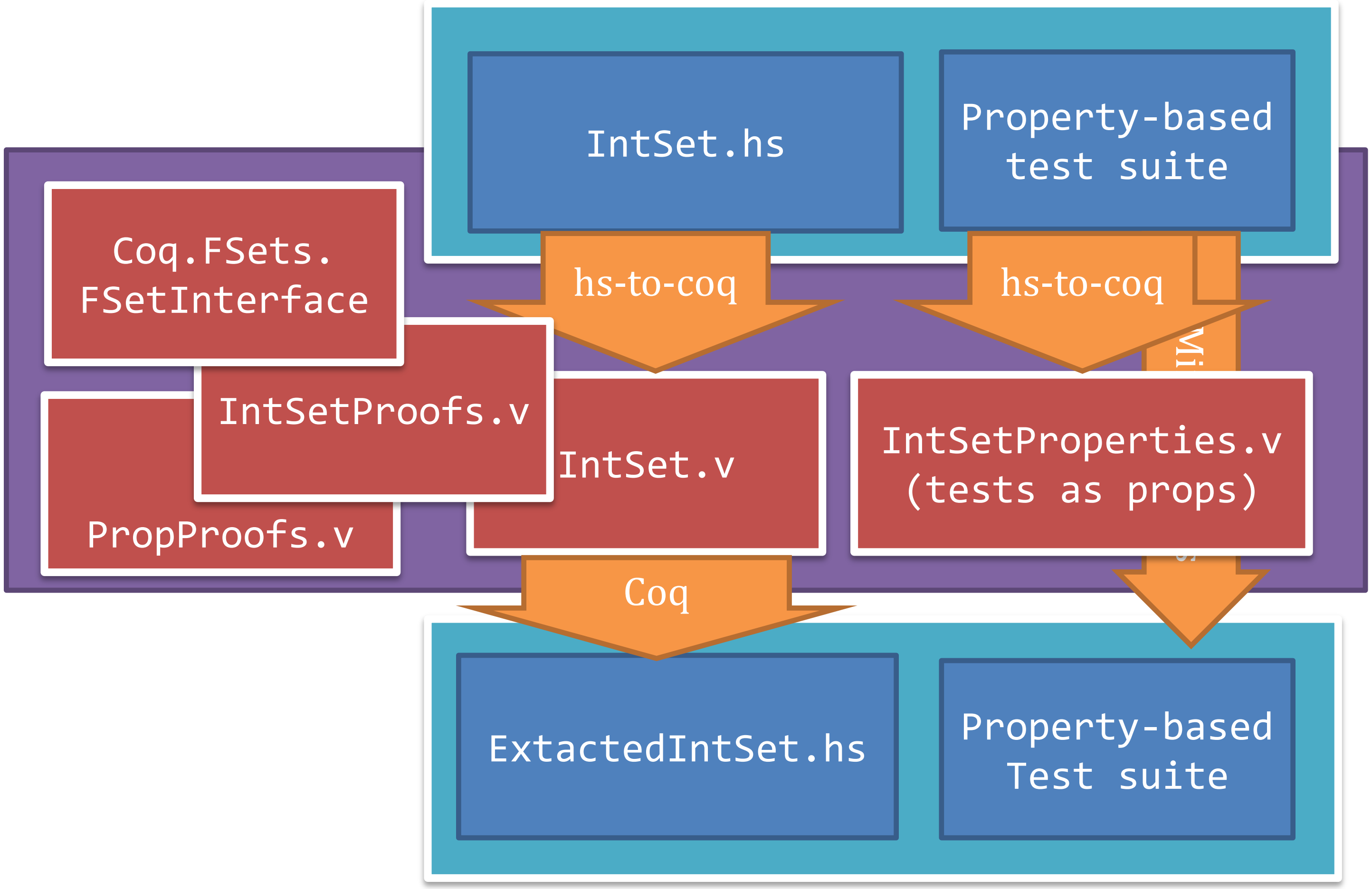
3. Even if we can do the proofs, do they mean anything about the Haskell source?

Case study: containers

- Popular Haskell libraries: Data.Set and Data.IntSet
- Used by GHC Core language implementation
- What did we prove?
  - Invariants in the source file comments (ensures the balance properties)
  - Mathematical specification (both our own and FSetInterface)
  - Quickcheck properties interpreted as theorems
  - GHC Rewrite rules

Experience Report: Ready, Set, Verify! Applying hs-to-coq to real-world Haskell code
Joachim Breitner, Antal Spector-Zabusky, Yao Li, Christine Rizkallah, John Wiegley, Stephanie Weirich
ICFP 2018 (cond. acc.)

Containers case study



IntSet.hs

Property-based test suite

Coq.FSets.FSetInterface

hs-to-coq

hs-to-coq

Mi

IntSetProofs.v

PropProofs.v

IntSet.v

IntSetProperties.v (tests as props)

Coq

ExtactedIntSet.hs

Property-based Test suite

What did we learn?

1. We can translate the library*
2. We can prove what we want to prove**
3. Output is semantically equivalent (as far as we can tell by testing)
4. Haskell code is functionally correct ☺

*Need to address partiality

**We "edit" the code during translation in support of proofs

Partiality: Unsound

```
head :: [a] -> a
head (x:_) = x
head [] = error "head: empty list"
```

```
Axiom error : forall {a} , String -> a.

Definition head {a}
    (xs : list a) : a :=
  match xs with
  | (x::_) => x
  | _      => error "head: empty list"
  end.
```

Partiality: Annoying

```
head :: [a] -> a
head (x:_) = x
head [] = error "head: empty list"
```

```
Inductive Partial (a:Type) :=
  | return : a -> Partial a
  | error  : String -> Partial a
  | …
Definition head {a} (xs : list a) : Partial a :=
  match xs with
  | (x::_) => return x
  | _      => error "head: empty list"
  end.
```

Partiality: Pragmatic

```
head :: [a] -> a
head (x:_) = x
head [] = error "head: empty list"
```

```
Definition error : forall {a} `{Default a},
                      String -> a := default.
Definition head {a} `{Default a}
    (xs : list a) : a :=
  match xs with
  | (x::_) => x
  | _      => error "head: empty list"
  end.
```

☞ "default" is an opaque definition and proofs must work for any value of the appropriate type. This is almost a requirement that it occurs in dead code.

A Formalization Gap is a *good* thing

- Machine integers are fixed width. Do we want to reason about overflow?
- No!
  - In Data.Set, Ints track size of tree for balance
  - GHC uses Data.IntSet to generate unique names
  - Both cases will run out of memory before overflow
- Control translation with hs-to-coq rewrites
  - type GHC.Num.Int = Coq.ZArith.BinNum.Z
  - Formalization gap is explicit & recorded

A Formalization Gap is a *good* thing

- Machine integers store positive and negative numbers. Do we want that?
- No!
  - In Data.Set, Ints track size of tree for balance
  - GHC uses Data.IntSet to generate unique names
  - Both cases never need to store negative numbers
- Control translation with hs-to-coq rewrites
  - type GHC.Num.Int = Coq.NArith.BinNat.N
  - Formalization gap is explicit & recorded

What about GHC?

Questions about GHC

1. Is there enough code *in GHC* that we can translate to make this approach worthwhile?

2. Even if we can find code to translate, is the result suitable for verification?

3. Even if we can do the proofs, do they mean anything about the GHC implementation? (Note: Core plug-in option available)

Core Spec

GHC: Current status

- Base libraries (9k loc)
  - 45 separate modules
  - Some written by-hand: GHC.Prim, GHC.Num, GHC.Tuple
  - Most translated: GHC.Base, Data.List, Data.Foldable, Control.Monad, etc.
- Containers (6k loc)
  - Translated & (mostly) verified: 4 modules
  - (Data.Set, Data.Map, Data.IntSet, Data.IntMap)
- GHC, version 8.4.1 (19k loc)
  - 55 modules so far (327 modules total in GHC, but we won't need them all)
  - hs-to-coq edits (2k LOC)
- *First verification goal*: Exitify compiler pass

Core AST

```
data Expr b
   = Var  Id
   | Lit  Literal
   | App  (Expr b) (Arg b)
   | Lam  b (Expr b)
   | Let  (Bind b) (Expr b)
   | Case (Expr b) b Type
          [Alt b]
   | Cast (Expr b) Coercion
   | Tick (Tickish Id) (Expr b)
   | Type Type
   | Coercion Coercion
    deriving Data
data Bind b =
    NonRec b (Expr b)
  | Rec [(b, (Expr b))]
   deriving Data
```

```
Inductive Expr b : Type
  := Mk_Var : Id -> Expr b
   | Lit : Literal -> Expr b
   | App :
       Expr b -> Arg b -> Expr b
   | Lam : b -> Expr b -> Expr b
   | Let :
      Bind b -> Expr b -> Expr b
   | Case : Expr b -> b -> unit
       -> list (Alt b) -> Expr b
   | Cast :
       Expr b -> unit -> Expr b
   | Tick : Tickish Id
       -> Expr b -> Expr b
   | Type_ : unit -> Expr b
   | Coercion : unit -> Expr b
with Bind b : Type
  := NonRec : b -> Expr b
                -> Bind b
   |  Rec : list (b * (Expr b))
               -> Bind b
```

Core Optimization : Exitify

```
-- | Given a recursive group of a joinrec, identifies
--   “exit paths” and binds them as
--   join-points outside the joinrec.

exitify :: InScopeSet -> [(Var,CoreExpr)] ->
           (CoreExpr -> CoreExpr)
exitify in_scope pairs =
    \body -> mkExitLets exits (mkLetRec pairs' body)
  where
     pairs' = …   // updated recursive group
     exits  = …   // exit paths

-- 215 LOC, incl comments
```

- Requires moving code from one binding scope to another
- First proof: show that well-scoped terms stay well-scoped

Bug found!

- Exitify does not always produced well-scoped code
  - Missed by GHC test suite
  - Perhaps not exploitable at source level
- Fixed in GHC HEAD
  - Proofs updated this week
- What is the general workflow?
  - Always work on HEAD? Maintain separate branch?
  - Axiomatize failing lemma?
  - Fix code via hs-to-coq edits?

Conclusion & More questions

Let's take advantage of the semantic similarity of Haskell and Gallina for developing verified compilers

- How far can we push this approach?
- Can we get good performance of extracted code? (And plug back into GHC?)
- Can we say anything about linking with nonverified code?

Back up slides…

Why not use CoInductive?

- Another formalization gap
  - Haskell datatypes are co-inductive by default
- But inductive reasoning is useful for compilers and languages
  - Termination of functions depends on decreasing size of data structure
- This is an example of an invariant about the core language
  - We assume it never needs to work with infinite terms, and prove that it never generates infinite terms
  - Never going to create an AST term with an "infinite" number of lambda expressions

What's in GHC Core?

- Additional general purpose libraries
  - Bag, State, Maybes, Pair, FiniteMap, OrdList, MonadUtils, BooleanFormula, …
- Compiler-specific utilities
  - SrcLoc, Module, DynFlags, Constants,
  - Unique, UniqSupply, UniqSet, UniqFM, …
- Core AST representation
  - IdInfo, Var, VarSet, VarEnv, Name, Id, Demand
  - Class, TyCon, DataCon, **CoreSyn**
- Core operations and optimization
  - CoreFVs, CoreSubst, CallArity, CoreArity,
  - **Exitify**

Exitify example

Example:

```
let t = foo bar
joinrec
    go 0     x y = t (x*x)
    go (n-1) x y = jump go (n-1) (x+y)
in …
```

We'd like to inline `t`, but that does not happen: Because t is a thunk and is used in a recursive function, doing so might lose sharing in general. In this case, however, `t` is on the _exit path_ of `go`, so called at most once.

Example result:

```
let t = foo bar
join exit x = t (x*x)
joinrec
    go 0     x y = jump exit x
    go (n-1) x y = jump go (n-1) (x+y)
in …
```

Now `t` is no longer in a recursive function, and good things happen!