Reasonable Agda Is Correct Haskell:

Writing Verified Haskell using **agda2hs**

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Motivation: issues with current program extractors

MAlonzo covers the entirety of Agda, but produces unreadable code:

```
insert : Nat → Tree → Tree
insert x Leaf = Node x Leaf Leaf
insert x (Node y l r) =
  case compare x y of λ where
    (LT _) → Node y (insert x l) r
    (EQ _) → Node y l r
    (GT _) → Node y l (insert x r)
{-# COMPILE AGDA2HS insert #-}
```

```
d_insert_1494 :: Integer -> Integer -> Integer
              -> T_Tree_1340 -> T__'8804'__1324
              -> T__'8804'__1324 -> T_Tree_1340
d_insert_1494 ~v0 ~v1 v2 v3 ~v4 ~v5 = du_insert_1494 v2 v3
du_insert_1494 :: Integer -> T_Tree_1340 -> T_Tree_1340
du_insert_1494 v0 v1 = case coe v1 of
  C_Leaf_1348 ->
    coe C_Node_1352 (coe v0) (coe C_Leaf_1348)
      (coe C_Leaf_1348)
  C_Node_1352 v2 v3 v4 ->
    coe MAlonzo.Code.Haskell.Prim.du_case_of__54
      (coe d_compare_1474 (coe v0) (coe v2))
      (coe du_'46'extendedlambda0_1514 (coe v0) (coe v2)
        (coe v3) (coe v4))
  _ -> MAlonzo.RTE.mazUnreachableError
```

Motivation: issues with current program extractors

Coq extracts more reabable code, but still does not readily support typeclasses:

```
Class Monoid (a : Set) :=
  { mempty  : a
  ; mappend : a -> a -> a }.

Instance MonoidNat : Monoid nat :=
  { mempty := 0
  ; mappend i j := i + j }.

Fixpoint sumMon {a} `{Monoid a}
  (xs : list a) : a :=
  match xs with
  | [] => mempty
  | x :: xs => mappend x (sumMon xs)
  end.
```

```
data Monoid a = Build_Monoid a (a -> a -> a)

mempty :: (Monoid a1) -> a1
mempty = ...
mappend :: (Monoid a1) -> a1 -> a1 -> a1
mappend = ...
monoidNat :: Monoid Nat
monoidNat = Build_Monoid O add

sumMon :: (Monoid a1) -> (List a1) -> a1
sumMon h xs = case xs of {
  ([]) -> mempty h;
  (:) x xs0 -> mappend h x (sumMon h xs0)}
```

Goals

1. Writing Haskell-like Agda (no need to cover the whole source language)
2. Verify your program using Agda's dependent types

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New point in the design space, enabled by:

- Agda very *similar* to Haskell + = ❤️
- Agda's *dependent type system*
- Agda's support for *erasure*

\+ allows for intrinsic verification!

Tree example (extrinsic version)

```agda
data Tree : Set where
  Leaf  : Tree
  Node : Nat → Tree → Tree → Tree
{-# COMPILE AGDA2HS Tree #-}

insert : Nat → Tree → Tree
insert x Leaf = Node x Leaf Leaf
insert x (Node y l r) =
  case compare x y of λ where
    (LT _) → Node y (insert x l) r
    (EQ _) → Node y l r
    (GT _) → Node y l (insert x r)
{-# COMPILE AGDA2HS insert #-}
```

```haskell
data Tree = Leaf
          | Node Natural Tree Tree

insert :: Natural -> Tree -> Tree
insert x Leaf = Node x Leaf Leaf
insert x (Node y l r)
  = case compare x y of
        LT -> Node y (insert x l) r
        EQ -> Node y l r
        GT -> Node y l (insert x r)
```

Tree example (extrinsic proofs)

```
                    ⋮
@0 _≤_≤_ : Nat → Tree → Nat → Set
l ≤ Leaf          ≤ u = l ≤ u
l ≤ Node x tˡ tʳ ≤ u = (l ≤ tˡ ≤ x) × (x ≤ tʳ ≤ u)

@0 insert-correct : ∀ {t x l u} → l ≤ t ≤ u
  → l ≤ x → x ≤ u → l ≤ insert x t ≤ u
insert-correct {Leaf} _ l≤x x≤u = l≤x , x≤u
insert-correct {Node y tˡ tʳ} {x} (IHˡ , IHʳ) l≤x x≤u
  with compare x y
... | LT x≤y  = insert-correct IHˡ l≤x x≤y , IHʳ
... | EQ refl = IHˡ , IHʳ
... | GT y≤x = IHˡ , insert-correct IHʳ y≤x x≤u
```

Tree example (intrinsic version)

```
data Tree (@0 l u : Nat) : Set where
  Leaf  : (@0 pf : l ≤ u) → Tree l u
  Node : (x : Nat) → Tree l x → Tree x u → Tree l u
{-# COMPILE AGDA2HS Tree #-}
insert : {@0 l u : Nat} (x : Nat) → Tree l u
  → @0 (l ≤ x) → @0 (x ≤ u) → Tree l u
insert x (Leaf _) l≤x x≤u =
  Node x (Leaf l≤x) (Leaf x≤u)
insert x (Node y l r) l≤x x≤u =
  case compare x y of λ where
    (LT x≤y)  → Node y (insert x l l≤x x≤y) r
    (EQ x≡y) → Node y l r
    (GT y≤x) → Node y l (insert x r y≤x x≤u)
{-# COMPILE AGDA2HS insert #-}
```

```haskell
data Tree = Leaf
          | Node Natural Tree Tree

insert :: Natural -> Tree -> Tree
insert x Leaf = Node x Leaf Leaf
insert x (Node y l r)
  = case compare x y of
      LT -> Node y (insert x l) r
      EQ -> Node x l r
      GT -> Node y l (insert x r)
```

Primitives

- Export lowercase type variables to feel like home (i.e. variable $a\ b\ c \cdots$: Set):

  $\mathrm{id} : a \longrightarrow a$

  $\mathrm{id}\ x = x$

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  e.g. Agda.Builtin.Nat $\leftrightarrow$ `Numeric.Natural`

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- Match Agda built-ins to Haskell built-ins:

  e.g. Agda.Builtin.Nat ↔ `Numeric.Natural`

- If not available in Agda, define them:

```
infix -2 if_then_else_
if_then_else_ : Bool → a → a → a
if False then x else y = y
if True then x else y = x
```

Primitives

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  ```
  id : a → a
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REMEMBER

We want to cover as many Haskell features as possible, not Agda features.

Prelude

Port Haskell's Prelude, staying faithful to the original functionality.

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```
error : (@0 i : ⊥) → String → a
error ()

head : (xs : List a) {@0 _ : NonEmpty xs} → a
head (x :: _) = x
head [] {p}   = error i "empty list"
  where @0 i : ⊥
         i = case p of λ ()
{-# COMPILE AGDA2HS head #-}
```

```haskell
head :: [a] -> a
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Prelude

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head : (xs : List a) {@0 _ : NonEmpty xs} → a
head (x ∷ _) = x
head [] {p}   = error i "empty list"
  where @0 i : ⊥
           i = case p of λ ()
{-# COMPILE AGDA2HS head #-}
```

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

Don't forget

On the Haskell side, we can feed `head` arbitrary input!

Typeclasses

Correspondence with Agda's **instance arguments**.

- class definitions $\sim$ record types
- instance declarations $\sim$ record values
- constraints $\sim$ instance arguments

Typeclasses: class definitions ~ record types

```agda
record Monoid (a : Set) : Set where
  field
    mempty  : a
    mappend : a → a → a
    @0 left-identity  : mappend mempty x ≡ x
    @0 right-identity : mappend x mempty ≡ x
    @0 associativity  : mappend (mappend x y) z
                      ≡ mappend x (mappend y z)
open Monoid {{...}} public
{-# COMPILE AGDA2HS Monoid class #-}
```

```haskell
class Monoid a where
  mempty :: a
  mappend :: a -> a -> a
```

Typeclasses: instance declarations ∼ record values

```
instance
  MonoidNat : Monoid Nat
  MonoidNat = λ where
    .mempty         → 0
    .mappend i j    → i + j
    .left-identity  → ⋯
    .right-identity → ⋯
    .associativity  → ⋯
{-# COMPILE AGDA2HS MonoidNat #-}
```

```
instance Monoid Nat where
  mempty = 0
  mappend i j = i + j
```

Typeclasses: constraints ∼ instance arguments

```agda
sumMon : {{ Monoid a }} → List a → a
sumMon []        = mempty
sumMon (x ∷ xs) = mappend x (sumMon xs)
{-# COMPILE AGDA2HS sumMon #-}
```

```haskell
sumMon :: Monoid a => [a] -> a
sumMon [] = mempty
sumMon (x : xs) = mappend x (sumMon xs)
```

Default methods & minimal complete definitions

```agda
record Show (a : Set) : Set where
  field show      : a → String
        showsPrec : Nat → a → ShowS
        showList  : List a → ShowS
record Show₁ (a : Set) : Set where
  field showsPrec : Nat → a → ShowS
  show x = showsPrec 0 x ""
  showList = defaultShowList (showsPrec 0)
record Show₂ (a : Set) : Set where
  field show : a → String
  showsPrec _ x s = show x ++ s
  showList = defaultShowList (showsPrec 0)
open Show {{...}}
{-# COMPILE AGDA2HS Show class Show₁ Show₂ #-}
```

```haskell
class Show a where
  show :: a -> String
  showsPrec :: Nat -> a -> ShowS
  showList :: [a] -> ShowS
  {-# MINIMAL showsPrec | show #-}
  show x = showsPrec 0 x ""
  showList = defaultShowList
             (showsPrec 0)
  showsPrec _ x s = show x ++ s
```

Minimal Instance

```
instance
  ShowMaybe : {{Show a}} → Show (Maybe a)
  ShowMaybe {a = a} = record {Show₁ s₁}
    where
      s₁ : Show₁ (Maybe a)
      s₁ .Show₁.showsPrec n = λ where
        Nothing → showString "nothing"
        (Just x)  → showParen True
          ( showString "just " ∘ showsPrec 10 x )
{-# COMPILE AGDA2HS ShowMaybe #-}
```

```haskell
instance (Show a)
      => Show (Maybe a) where
  showsPrec n = \case
    Nothing -> showString "nothing"
    (Just x) -> showParen True
      (showString "just " . showsPrec 10 x)
```

IOG's Cardano blockchain

- currently the 8^{th} largest by market cap
- smart contracts written in Plutus, based on System F_ω^μ
- implemented in Haskell
- tested against Agda formalization

agda2hs in the wild

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IOG use case: type renaming & substitution

```agda
data Kind : Set where
  Star   :  Kind
  _:=>_  :  Kind → Kind → Kind
data Type (n : Set) : Set where
  TyVar    : n → Type n
  TyFun    : Type n → Type n → Type n
  TyForall : Kind → Type (Maybe n) → Type n
  TyLam    : Type (Maybe n) → Type n
  TyApp    : Type n → Type n → Kind → Type n
ren : (n → n') → Type n → Type n'
sub : (n → Type n') → Type n → Type n'
```

```haskell
data Kind
  = Star
  | Kind :=> Kind

data Type n
  = TyVar n
  | TyFun (Type n) (Type n)
  | TyForall Kind (Type (Maybe n))
  | TyLam (Type (Maybe n))
  | TyApp (Type n) (Type n) Kind

ren :: (n -> n') -> Type n -> Type n'
sub :: (n -> Type n') -> Type n -> Type n'
```

IOG use case: Laws

ren is a *functorial map* on Type.

- ren-id: $(ty : \mathsf{Type}\ n) \longrightarrow \mathsf{ren}\ \mathsf{id}\ ty \equiv ty$
- ren-comp: $(ty : \mathsf{Type}\ n)\ (\rho : n \longrightarrow n')\ (\rho' : n' \longrightarrow n'')$
  $\longrightarrow \mathsf{ren}\ (\rho' \circ \rho)\ ty \equiv \mathsf{ren}\ \rho'\ (\mathsf{ren}\ \rho\ ty)$

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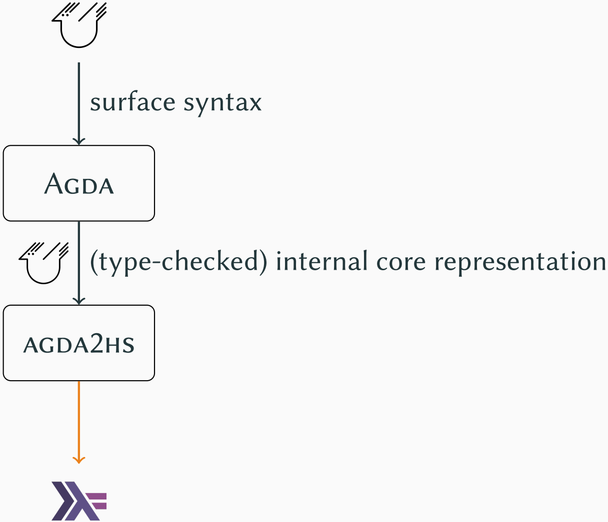
sub is a *monadic bind* on Type.

- sub-id: $(t : \mathsf{Type}\ n) \longrightarrow \mathsf{sub}\ \mathsf{TyVar}\ t \equiv t$
- sub-var: $(x : n)\ (\sigma : n \longrightarrow \mathsf{Type}\ n') \longrightarrow \mathsf{sub}\ \sigma\ (\mathsf{TyVar}\ x) \equiv \sigma\ x$
- sub-comp: $(ty : \mathsf{Type}\ n)\ (\sigma : n \longrightarrow \mathsf{Type}\ n')\ (\sigma' : n' \longrightarrow \mathsf{Type}\ n'')$ $\longrightarrow \mathsf{sub}\ (\mathsf{sub}\ \sigma' \circ \sigma)\ ty \equiv \mathsf{sub}\ \sigma'\ (\mathsf{sub}\ \sigma\ ty)$

Implementation

https://github.com/agda/agda2hs



Implementation: where clauses

Surface

$\mathsf{f} : \mathsf{Nat} \longrightarrow \mathsf{Nat}$

$\mathsf{f}\ x = \mathsf{go}$

  where

    $\mathsf{go} : \mathsf{Nat}$

    $\mathsf{go} = \mathsf{TODO}$

    -- may use x

Intermediate

$\mathsf{go} : \mathsf{Nat} \longrightarrow \mathsf{Nat}$

$\mathsf{go}\ x = \mathsf{TODO}$

$\mathsf{f} : \mathsf{Nat} \longrightarrow \mathsf{Nat}$

$\mathsf{f}\ x = \mathsf{go}\ x$

Output

```
f :: Natural -> Natural
f x = go
  where
    go :: Natural
    go = TODO
```

Correctness

Is our translation **sound**?

1. Agda that typechecks produces valid Haskell
2. Translation preserves behaviour/semantics

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c.f. Cockx's NWO grant: *A Trustworthy and Extensible Core Language for Agda*

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- Trust the ported Prelude and defined primitives
- Ensure all dependent types appear under *erased* positions
  - enforced by the agda2hs backend
- Translation of each language construct has equivalent behaviour
  - most cases blindingly obvious

NB

total functions + strong normalisation $\Rightarrow$ evaluation order doesn't matter

Future work

Still many unsupported Haskell features:

- GADTs
- pattern guards, views
- 32-bit arithmetic
- Monadic code
- Infinite data
- Non-termination, general recursion

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- GADTs $\sim$ covered by dependent types $\rightarrow$ identify subset
- pattern guards, views $\sim$ use with-matching
- 32-bit arithmetic $\sim$ first add to Agda itself
- Monadic code $\sim$ still need to reverse desugaring
- Infinite data $\sim$ coinductive types
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Extra goodies:

- Generate **runtime checks** for decidable properties
- **QuickCheck** postulated properties
- HS2AGDA: inverse translation $\Rightarrow$ streamline porting of **existing** libraries

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Extra goodies:

- Generate **runtime checks** for decidable properties
- **QuickCheck** postulated properties
- HS2AGDA: inverse translation $\Rightarrow$ streamline porting of **existing** libraries

More **applications** + **comparisons** with LiquidHaskell, `hs-to-coq`, etc..

Shameless plug https://wiki.portal.chalmers.se/agda/Main/AIMXXXI

AGDA2HS was developed during the last two **Agda Implementors' Meetings**

- biannual event where Agda users of all levels hack on Agda, its ecosystem, etc..

AIM XXXI in Edinburgh November 10-16, will include:

- talks
- code sprints
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Questions?