A Framework for the Automatic Formal Verification of Refinement from COGENT to C

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ITP, Nancy, France
24th of August 2016

Cogent Project: Overall Story

Motivation

File systems are too important to remain unverified

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Sounds good, but **HOW**?

Languages, Type Systems, and Certifying Compilers

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- Design a restricted purely functional language, expressive enough to describe most of the file system code
- Use type systems techniques (linear types) to enforce properties such as memory safety at compile time
- Create a certifying compiler to automate the low level "boring" parts of the verification

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  - relied on automating large parts of the verification

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But First Let's Get Familiar with COGENT

The COGENT Language

- linearly typed, restricted, polymorphic, higher-order, purely functional language
- has typical **let**, **if**, ..., for records **take**, **put** (linearity)
- COGENT programs rely on an external library of abstract data types (ADTs) for data structures like arrays, lists, red-black trees, etc.
- loops are implemented as iterators over ADTs

Linear Type System

- Variables with a linear type must be used exactly once.
- COGENT's linear type system:
  - allows generating efficient imperative code with in-place updates
  - assists memory management
  - prevent errors such as use-after-free, memory leaks, pointer mismanagement in error-handling, etc.

COGENT Example: Flip

$$
\begin{array}{l}
\mathit{flip} \;\; :: \{\mathrm{f} \;\; :: \texttt{U8}\}\ \texttt{w} \rightarrow \{\mathrm{f} \;\; :: \texttt{U8}\}\ \texttt{w} \\
\mathit{flip}\ x = \\
\quad \textbf{take}\ x'\ \{\mathrm{f} = y\} = x \\
\quad \textbf{in if}\ y == 0 \\
\qquad \textbf{then put}\ x'.\mathrm{f} := 1 \\
\qquad \textbf{else put}\ x'.\mathrm{f} := 0
\end{array}
$$

Linear Type System: Examples

Variables with a linear type must be used exactly once.

$$\begin{array}{l}\textbf{let}\ x\ =\ \mathit{allocData}\\ \textbf{and}\ y\ =\ x\\ \textbf{and}\ \_\ =\ \mathit{free}\ x\\ \textbf{in}\ y\end{array}$$

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Linear Type System: Examples

The linear type system enables the conversion from purely functional to imperative code with in-place memory update.

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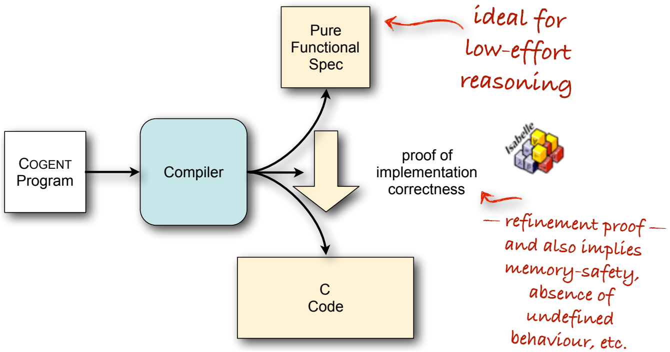
COGENT needs no garbage collector.

Why can we get away with type system and restrictions?

Idea

- Write most code in COGENT to simplify its verification
- Write a small part in C and verify it manually

Cogent: Certifying Compiler



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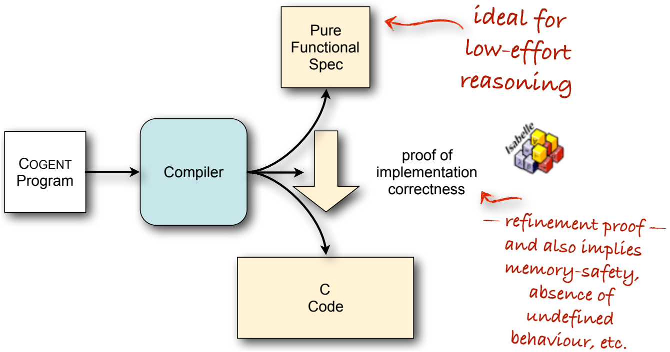

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Performance

- The performance of the generated C is similar to that of hand written C.

Cogent Compiler uses Pre-Existing Tools

Simpl [Schirmer 2005]

- Imperative language embedded into Isabelle/HOL

C-Parser [Norrish 2012]

- straightforward translation from C to Simpl

AutoCorres [Greenaway et al. 2012]

- converts Simpl to monadic representation in Isabelle/HOL
- verified simplifications
- output meant for manual reasoning
- we tweak AutoCorres to make its output more predictable (for automation on top)

How does the Certifying Compiler Automatically Generate Refinement Theorems and Proofs?

Cogent Example: Back to Flip

```
flip :: {f :: U8} w → {f :: U8} w
flip x =
   take x′ {f = y} = x
   in if y == 0
      then put x′.f := 1
      else put x′.f := 0
```

Cogent Example: Generated HOL and C Flip

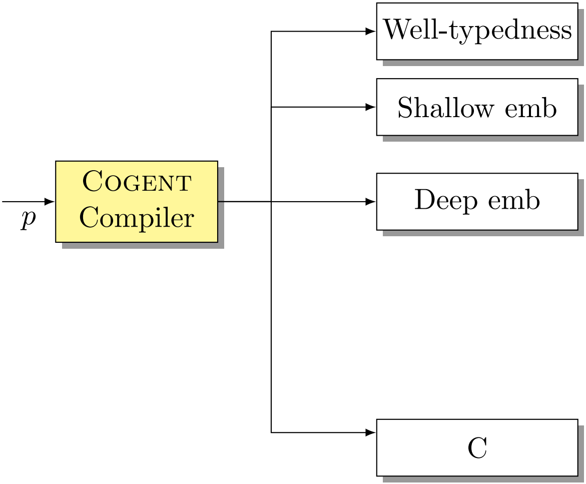
Functional Specification (HOL)

```
flip :: {f :: U8} → {f :: U8}
flip x =
  take x′ {f = y} = x
  in let tmp₁ = 0
     and tmp₂ = (y == tmp₁)
     in if tmp₂
        then let tmp₃ = 1
             and x″ = put x′.f := tmp₃
             in x″
        else let tmp₄ = 0
             and x″ = put x′.f := tmp₄
             in x″
```

C code (monadic representation)

```
flip_C :: rec₁ ptr ⇒ (rec₁ ptr, σ) nondet_monad
flip_C x = do
  guard (λσ. is-valid σ x);
  y ← gets (λσ. σ[r].f);
  tmp₁ ← return 0;
  tmp₂ ← return bool (y = tmp₁);
  tmp_result ← condition (bool tmp₂ ≠ 0)
      (do tmp₃ ← return 1;
          guard (λσ. is-valid σ x);
          modify (λσ. σ[x].f := tmp₃);
          return x od)
      (do tmp₄ ← return 0;
          guard (λσ. is-valid σ x);
          modify (λσ. σ[x].f := tmp₄);
          return x od);
  return tmp_result
  od
```

Overall Project: How did we structure refinement?



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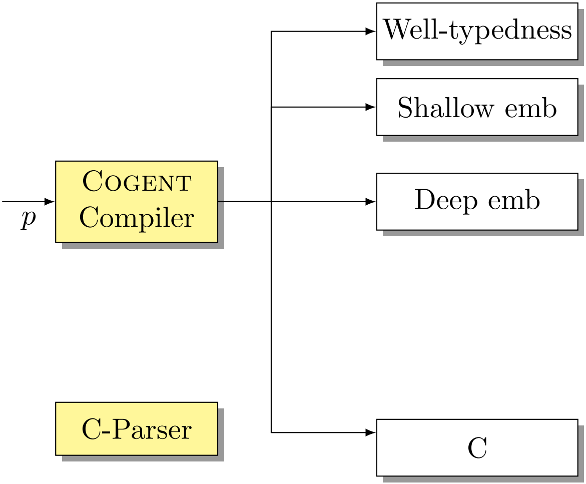

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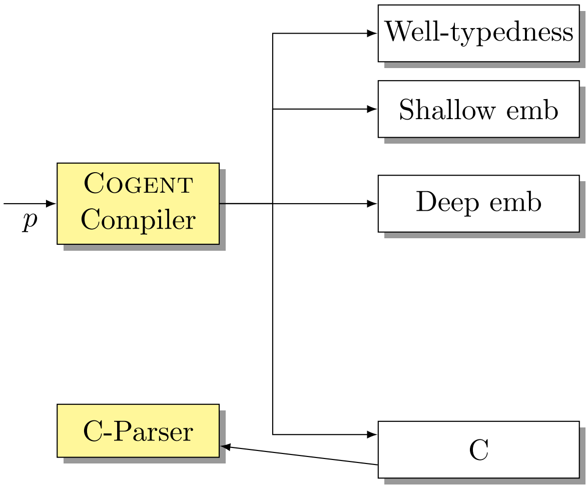

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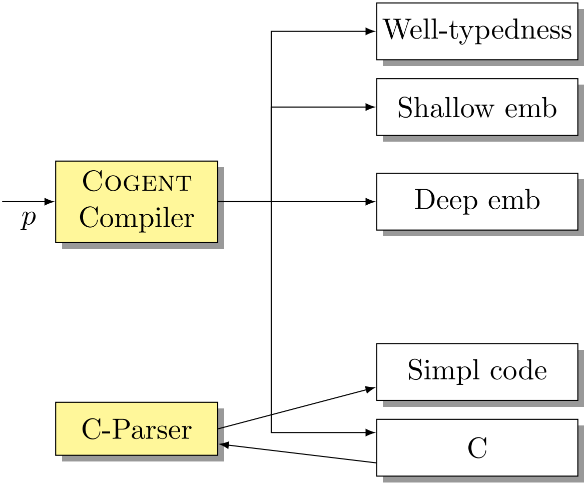

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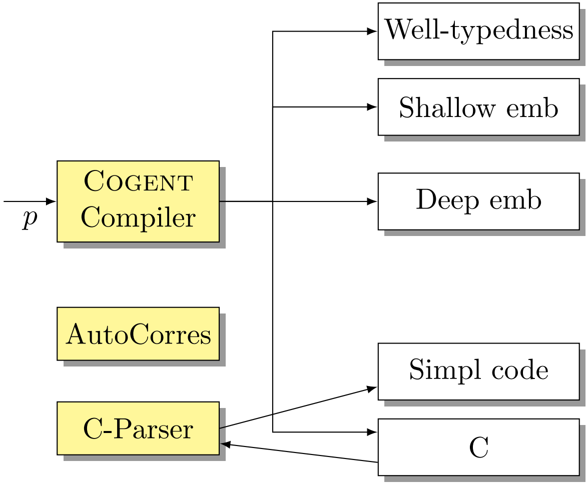

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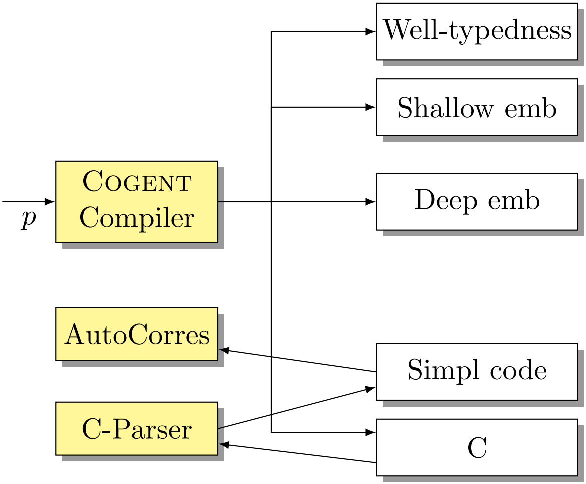

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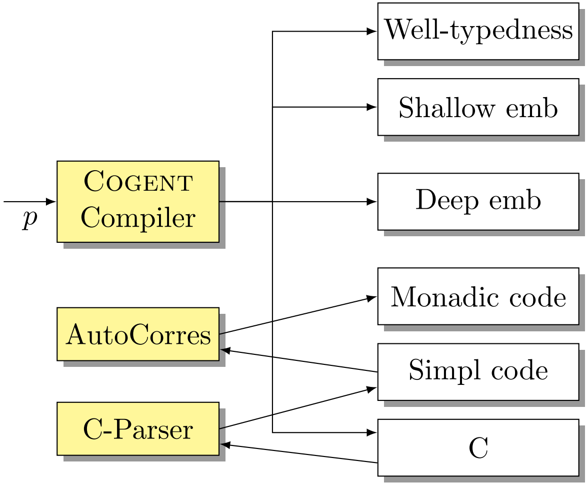

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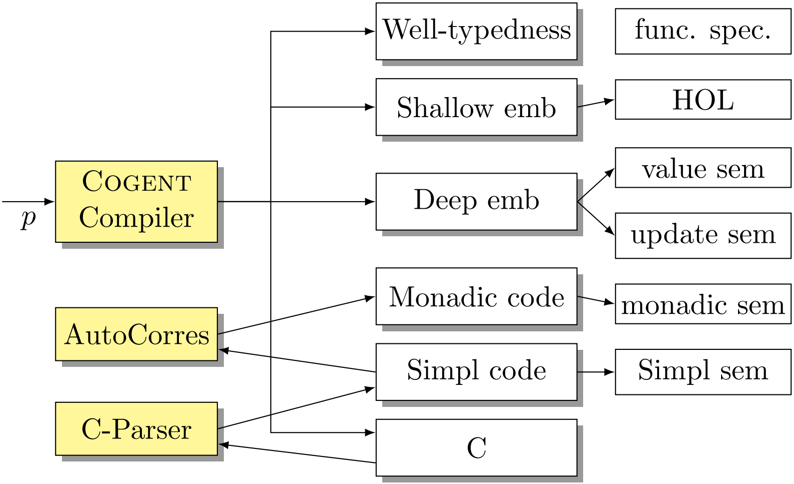

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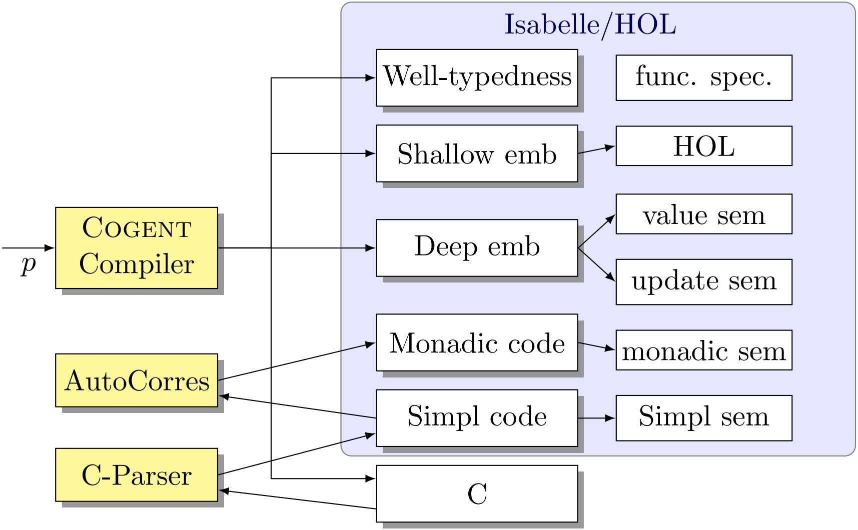

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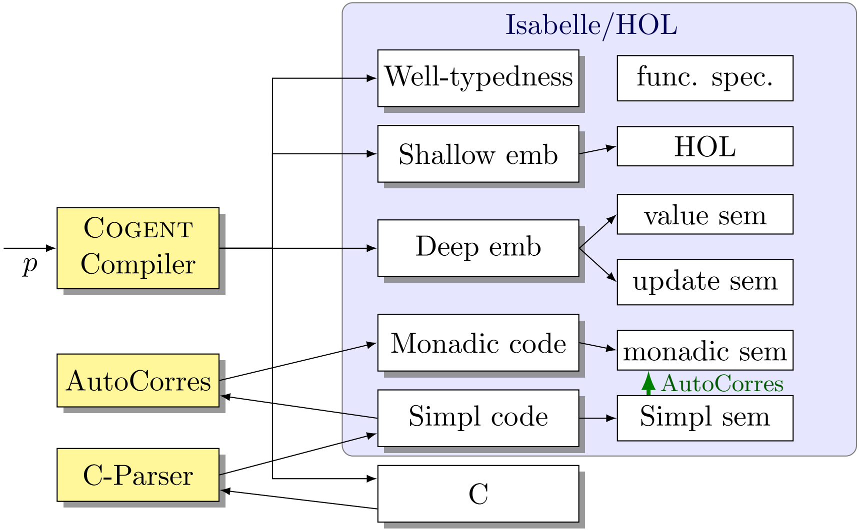

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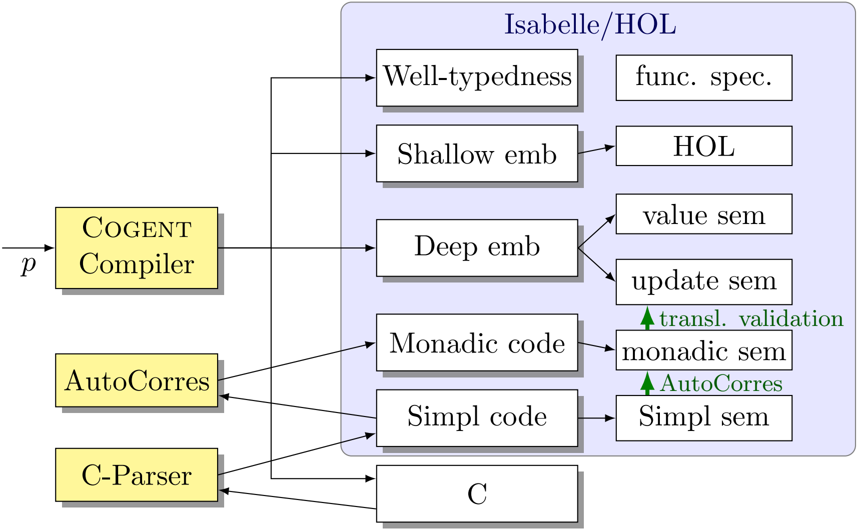

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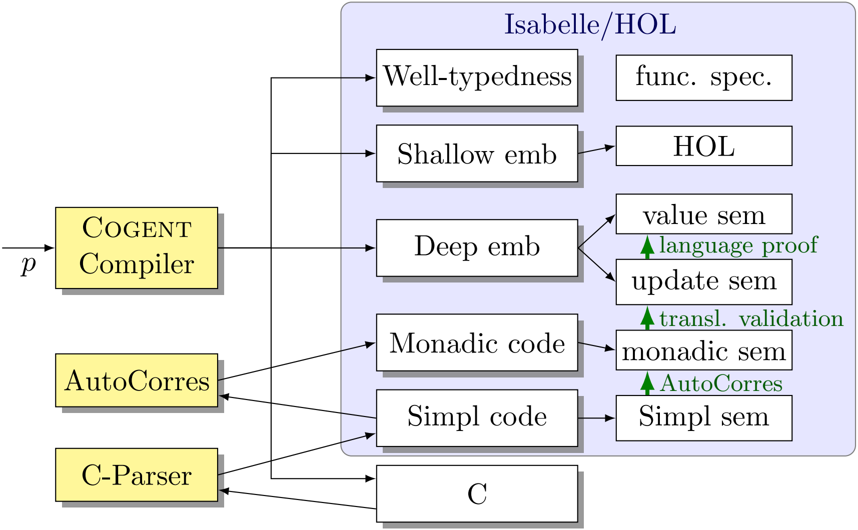

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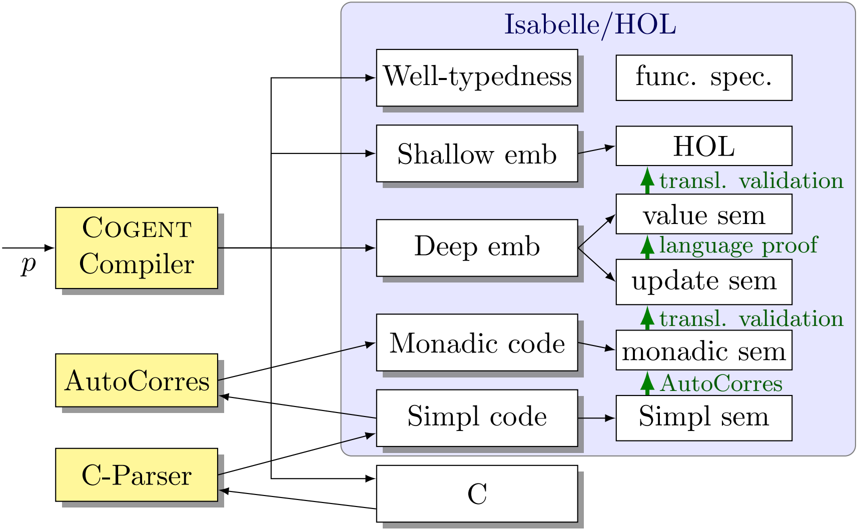

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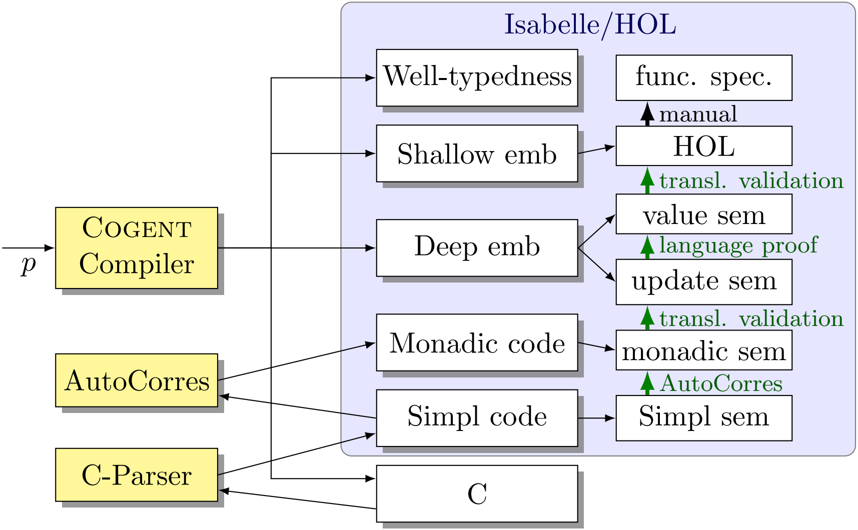

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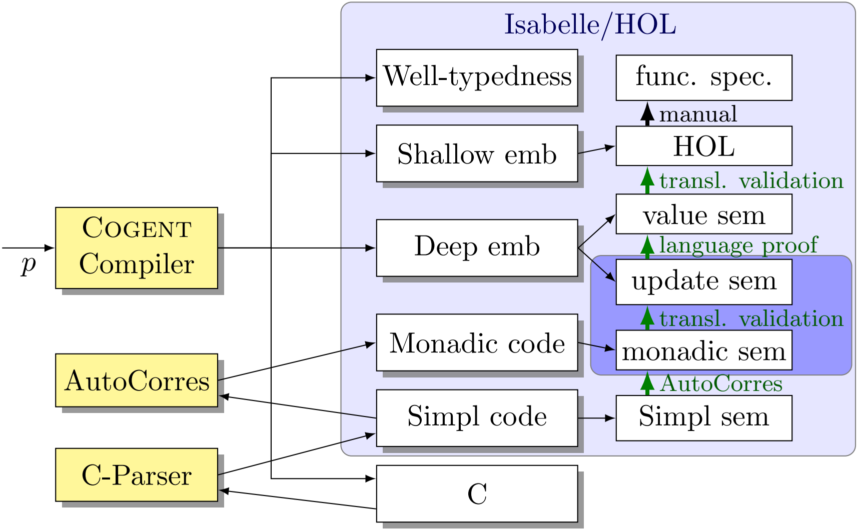

How did we prove refinement (update to monadic sem.)?

Data Relations and Refinement Predicate

- values
- types

- states
- statements

Theories and Automation

- refinement calculus
- well-typedness proof
- syntax directed proof automation

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Data Relations and Refinement Predicate

- values
- types
  - several COGENT types correspond to the same C type
  - partial type erasure removes linearity from COGENT type
- states
- statements (**corres** R e p_m U Γ μ σ)

Theories and Automation

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Refinement Calculus: Var rule

$$\frac{(x \mapsto v_u) \in U \qquad \mathit{val\text{-}rel}\ v_u\ v_m}{\mathbf{corres}\ R\ x\ (\mathbf{return}\ v_m)\ U\ \Gamma\ \mu\ \sigma}\textsc{Var}$$

Refinement Calculus: If rule

$$\dfrac{\Gamma_1 \vdash c : \texttt{Bool} \qquad (\mathit{bool}\, c' = 0 \lor \mathit{bool}\, c' = 1) \\ c \text{ is a Cogent boolean equal to } (\mathit{bool}\ c' \neq 0) \\ \textbf{corres}\ R\ e_1\ e_1'\ U\ \Gamma_2\ \mu\ \sigma \qquad \textbf{corres}\ R\ e_2\ e_2'\ U\ \Gamma_2\ \mu\ \sigma}{\textbf{corres}\, R\, (\textbf{if}\ c\ \textbf{then}\ e_1\ \textbf{else}\ e_2) \\ (\textbf{do}\, x \leftarrow \textbf{condition}\ (\mathit{bool}\, c' \neq 0)\ e_1'\ e_2';\ \textbf{return}\, x\, \textbf{od})\, U\, (\Gamma_1\Gamma_2)\, \mu\, \sigma}\ \textsc{If}$$

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- Cogent compiler proves via an automated Isabelle tactic that the deep embedding of input program is well-typed
- proving refinement requires access to typing judgements of subexpressions of the program
- due to linear types, it is not easy to statically infer that subexpressions of a well-typed program are well-typed
- our proof automation then uses well-typedness theorems to discharge typing assumptions in refinement calculus

Proof Automation (for concrete program)

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- tactic compositionally applies syntax directed rules
- tactic uses well-typedness theorems to discharge typing assumptions
- refinement for foreign functions is assumed

Conclusion

- We developed a compositional refinement calculus and proof rules to create a fully automatic refinement certificate from Cogent to C.
- Through co-generation of code and proofs our framework significantly reduces the cost of reasoning about efficient C.
- It does so by discharging cumbersome safety obligations and providing an embedding more amenable to verification.
- Our framework was applied to two real world file systems.

Future work

- Speed C-Parser and AutoCorres for our very large dev.
    - `BilbyFs` generated code is $\approx$ `1.8 x` the size of `seL4`
- Add optimizations (additional to ones we get by using `gcc`)
- Verify a library of abstract data types

Meet the other Verification/PL Folks

Japheth Lim

Yutaka Nagashima

Thomas Sewell

Zilin Chen

Liam O'Connor

Toby Murray

Gabi Keller

Gerwin Klein

Now that you know about COGENT,
consider trying it out!

COGENT: co-generation of code and proofs significantly reduces the cost of reasoning about efficient C.

Thanks for Listening, Questions?