Trustworthy decompilation: Extracting models of machine code inside an ITP

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TEITP 2010

The GCD program in ARM machine code:

```
E1510002 B0422001 C0411002 01AFFFFB
```

Problems with machine code

Formal verification of machine code:

machine code

code

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correctness statement

$\{P\}\, code\, \{Q\}$

Problems with machine code

Formal verification of machine code:

ARM/x86/PowerPC model

⋮

(12100/4500/2100 lines)

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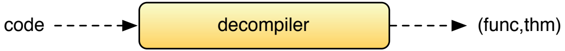
Contribution: tools/methods which

- expose as little as possible of the big models to the user;
- make non-automatic proofs independent of the models

Proposed solution

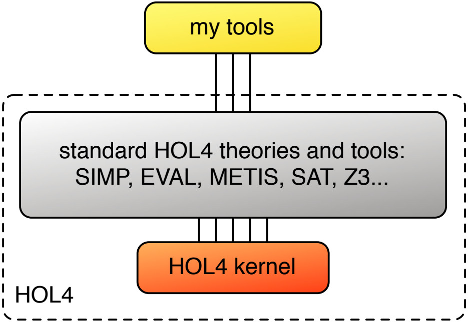


Decompiler:

- input: machine code
- output: function computed by code & certificate theorem

Trusted extension

My tools $=$ ML programs which steer HOL4 to a proof



Every proof passes the LCF-style logical kernel of HOL4.

This talk:

- explaining decompilation $\|$ demo
- pros/cons of HOL4

Models of machine languages

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Models of machine languages

Machine models borrowed from work by others:

ARM model, by Fox [ITP'10]

- covers practically all ARM instructions, for old and new ARMs
- extensively tested against real hardware

x86 model, by Sarkar et al. [POPL'09]

- covers all addressing modes in 32-bit mode x86
- includes approximately 30 instructions

PowerPC model, originally from Leroy [POPL'06]

- manual translation (Coq $\rightarrow$ HOL4) of Leroy's PowerPC model
- instruction decoder added

Hoare triple

Each model can be evaluated, e.g. ARM instruction `add r0,r0,r0` is described by theorem:

```
|- (ARM_READ_MEM ((31 >< 2) (ARM_READ_REG 15w state)) state =
    0xE0800000w) ∧ ¬state.undefined ⇒
   (NEXT_ARM_MMU cp state =
     ARM_WRITE_REG 15w (ARM_READ_REG 15w state + 4w)
     (ARM_WRITE_REG 0w
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As a total-correctness machine-code Hoare triple:

```
|- SPEC ARM_MODEL
    (aR 0w x * aPC p)
    {(p,0xE0800000w)}
    (aR 0w (x+x) * aPC (p+4w))
```

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```

Informal syntax for this talk:

$\{\,\mathrm{R0}\ x * \mathrm{PC}\ p\,\}$
p : E0800000
$\{\,\mathrm{R0}\ (x{+}x) * \mathrm{PC}\ (p{+}4)\,\}$

Demo.

Decompilation

Decompiler automates Hoare triple reasoning.

Example: Given some ARM machine code,

```
 0: E3A00000
 4: E3510000
 8: 12800001
12: 15911000
16: 1AFFFFFB
```

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the decompiler automatically extracts a readable function:

$$
\begin{aligned}
f(r_0, r_1, m) &= \text{let } r_0 = 0 \text{ in } g(r_0, r_1, m) \\
g(r_0, r_1, m) &= \text{if } r_1 = 0 \text{ then } (r_0, r_1, m) \text{ else} \\
&\qquad\quad \text{let } r_0 = r_0 + 1 \text{ in} \\
&\qquad\quad \text{let } r_1 = m(r_1) \text{ in} \\
&\qquad\qquad g(r_0, r_1, m)
\end{aligned}
$$

Decompilation, correct?

Decompiler automatically proves a certificate theorem:

$$f_{pre}(r_0, r_1, m) \Rightarrow$$
$$\{\,(\mathsf{R0}, \mathsf{R1}, \mathsf{M}) \text{ is } (r_0, r_1, m) * \mathsf{PC}\ p * \mathsf{S}\,\}$$
$$p : \mathtt{E3A00000\ E3510000\ 12800001\ 15911000\ 1AFFFFFB}$$
$$\{\,(\mathsf{R0}, \mathsf{R1}, \mathsf{M}) \text{ is } f(r_0, r_1, m) * \mathsf{PC}\ (p + 20) * \mathsf{S}\,\}$$

which informally reads:

for any initially value (r_0, r_1, m) in reg 0, reg 1 and memory,
the code terminates with $f(r_0, r_1, m)$ in reg 0, reg 1 and memory.

Decompilation, verification example

To verify code: prove properties of function f,

$$\forall x\ l\ a\ m.\ \ list(l, a, m) \ \Rightarrow\ f(x, a, m) = (length(l), 0, m)$$
$$\forall x\ l\ a\ m.\ \ list(l, a, m) \ \Rightarrow\ f_{pre}(x, a, m)$$

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Proof reuse: Given similar x86 and PowerPC code:

```
31C085F67405408B36EBF7
```

```
38A000002C140000408200107E80A02E38A500014BFFFFF0
```

which decompiles into f' and f'', respectively. Manual proofs above can be reused if $f = f' = f''$.

Demo.

Decompilation, algorithm

Algorithm:

1. derive a Hoare-triple for each instruction
2. find all paths through code
3. for each loop/sub-component:
   a. compose Hoare triples along each path
   b. merge resulting Hoare triples
   c. apply a loop rule, if necessary

The loop rule introduces a tail-recursive function, an instance of

$$\mathit{tailrec}(x) = \text{if } G(x) \text{ then } \mathit{tailrec}(F(x)) \text{ else } D(x)$$

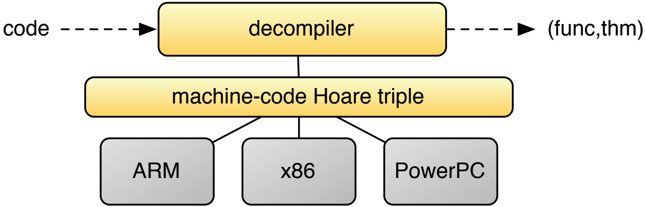
Decompiler, implementation

Implementation:

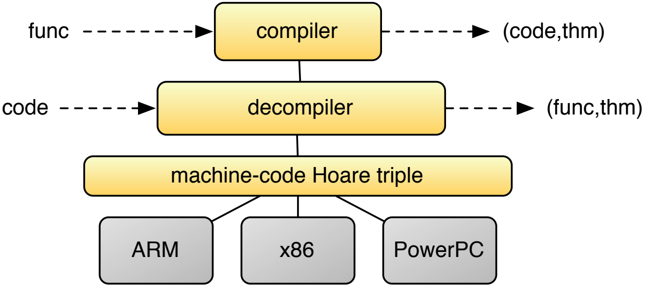
- ML program which fully-automatically performs forward proof,
- no heuristics and no dangling proof obligations,
- ‘smart’ tactics, e.g. `SIMP`, avoided to be robust.

Details in Myreen et al. [FMCAD’08].

Applications



Applications



Compiler

Synthesis often more practical. Given function f,

$$f(r_1) \;=\; \text{if } r_1 < 10 \text{ then } r_1 \text{ else let } r_1 = r_1 - 10 \text{ in } f(r_1)$$

our *compiler* generates ARM machine code:

```
E351000A     L:  cmp r1,#10
2241100A         subcs r1,r1,#10
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```
E351000A     L:  cmp r1,#10
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```

and automatically proves a certificate HOL theorem:

$$\vdash \;\{\, \text{R1 } r_1 * \text{PC } p * \text{s} \,\}$$
$$p : \texttt{E351000A 2241100A 2AFFFFFC}$$
$$\{\, \text{R1 } f(r_1) * \text{PC } (p{+}12) * \text{s} \,\}$$

Compilation example, cont.

One can prove properties of f since it lives inside HOL:

$$\vdash \ \forall x.\ f(x) = x \bmod 10$$

Compilation example, cont.

One can prove properties of f since it lives inside HOL:

$$\vdash \ \forall x.\ f(x) = x \text{ mod } 10$$

Properties proved of f translate to properties of the machine code:

$$\vdash \ \{\text{R1}\ r_1 * \text{PC}\ p * \text{s}\}$$
$$p : \texttt{E351000A 2241100A 2AFFFFFC}$$
$$\{\text{R1}\ (r_1 \text{ mod } 10) * \text{PC}\ (p{+}12) * \text{s}\}$$

Compilation example, cont.

One can prove properties of f since it lives inside HOL:

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Additional feature: the compiler can use the above theorem to extend its input language with: let $r_1 = r_1$ mod 10 in _

Additional feature: user-defined extensions

Using our theorem about mod, the compiler accepts:

$$
\begin{aligned}
g(r_1, r_2, r_3) \;=\; & \text{let } r_1 = r_1 + r_2 \text{ in} \\
& \text{let } r_1 = r_1 + r_3 \text{ in} \\
& \text{let } r_1 = r_1 \text{ mod } 10 \text{ in} \\
& \quad (r_1, r_2, r_3)
\end{aligned}
$$

Previously proved theorems can be used as building blocks for subsequent compilations.

Implementation

To compile function f:

1. generate, without proof, code from input f;
2. decompile, with proof, a function f' from generated code;
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Features:

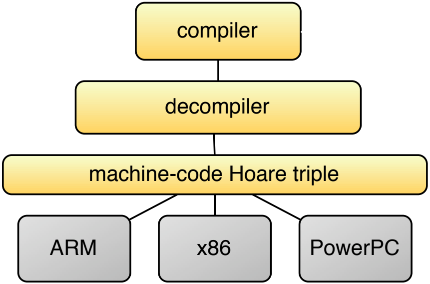
- code generation completely separate from proof
- supports many light-weight optimisations without any additional proof burden: instruction reordering, conditional execution, dead-code elimination, duplicate-tail elimination, ...
- allows for significant user-defined extensions

Details in Myreen et al. [CC'09]

Demo.

LISP case study

Verified LISP implementations via compilation.



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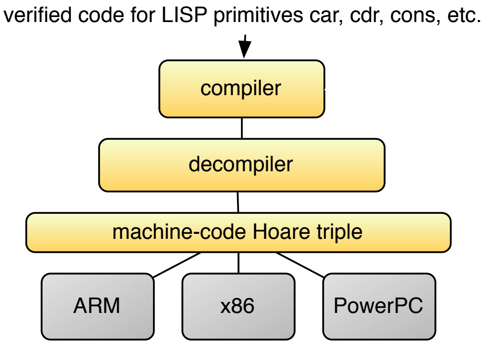

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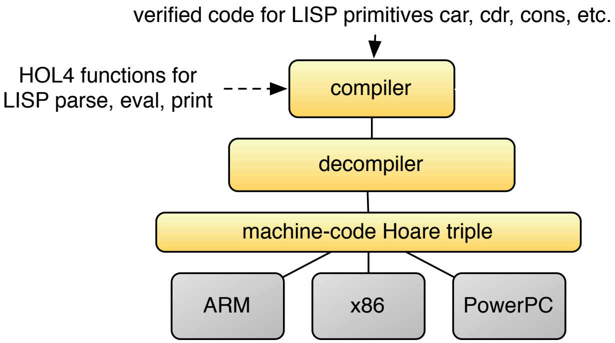

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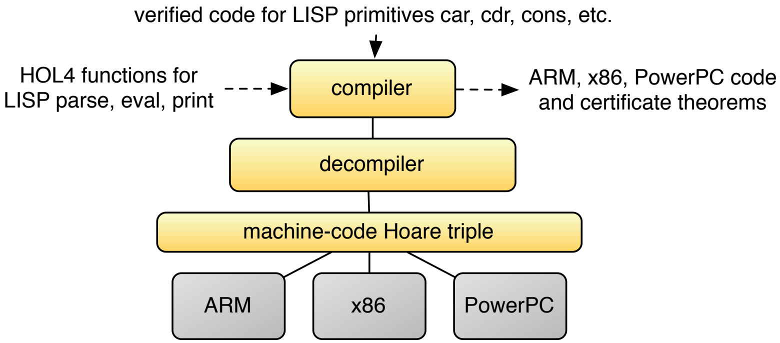

Demo.

Restrictions of decompilation

(De)compilation applicable only to programs where:

1. jumps are to fixed offsets or procedure returns,
2. code and data are kept separate, and
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Decompiler extensively used in proof of JIT compiler with:

1. code pointers,
2. self-modifying code, and
3. a non-deterministic ISA model.

Decompiler applied to ‘well-behaved’ sub-components.

This talk:

- explaining decompilation $\parallel$ demo
- pros/cons of HOL4

Pros/cons of HOL4

Pros:

- HOL4 is easily programmable
- lack of user interface — user at ML level
- easy to mix backwards/forwards reasoning
- conceptually simple

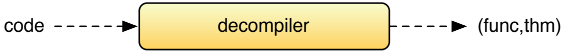
Cons:

- very space consuming, e.g. the term "$[1, 20, 3000]$" is represented by > 30 cons cells
- not automatic enough, not modular enough, ...

Talk summary

Decompilation:

- automates Hoare triple reasoning,
- extracts function computed by code,
- useful for verification and code synthesis.



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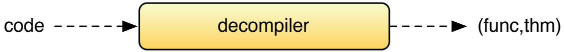

Questions?

(I can demo the verified Lisp or JIT on request.)