Trustworthy decompilation:
Extracting models of machine code inside an ITP

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The GCD program in ARM machine code:

```
E1510002 B0422001 C0411002 01AFFFFFFB
```
Problems with machine code

Formal verification of machine code:

machine code

\[ code \]
Problems with machine code

Formal verification of machine code:

```
\text{machine code} \quad \text{correctness statement}
\begin{array}{l}
\{P\} \text{ code } \{Q\}
\end{array}
```
Problems with machine code

Formal verification of machine code:

ARM/x86/PowerPC model

machine code

code

(correctness statement)

\{ P \} code \{ Q \}
Problems with machine code

Formal verification of machine code:

ARM/x86/PowerPC model

machine code

\[
\begin{array}{c}
\text{code} \\
(12100/4500/2100 \text{ lines}) \\
\end{array}
\]

correctness statement
\[
\{ P \} \text{ code } \{ Q \}
\]

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

Formal verification of machine code:

ARM/x86/PowerPC model

\[
\begin{array}{c}
\text{machine code} \\
\text{\hspace{1cm} code} \\
\text{(12100/4500/2100 lines)} \\
\end{array}
\]

\[
\begin{array}{c}
\text{correctness statement} \\
\{P\} \text{ code } \{Q\}
\end{array}
\]
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 → HOL4) of Leroy’s PowerPC model
- instruction decoder added
Hoare triple

Each model can be evaluated, e.g. ARM instruction
\texttt{add \textit{r0,r0,r0}} is described by theorem:

\begin{verbatim}
|- (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
(Arm_READ_REG 0w state + Arm_READ_REG 0w state) state))
\end{verbatim}
Hoare triple

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

$$|- (\text{ARM\_READ\_MEM (}(31 \gg 2) (\text{ARM\_READ\_REG 15w state})) \text{ state } = 0x\text{E0800000w}) \land \neg \text{state.undefined } \Rightarrow$$
$$\text{NEXT\_ARM\_MMU cp state } = \text{ARM\_WRITE\_REG 15w (ARM\_READ\_REG 15w state } + 4w)$$
$$\text{ARM\_WRITE\_REG 0w}$$
$$\text{ARM\_WRITE\_REG 0w state } + \text{ARM\_READ\_REG 0w state}) \text{ state})$$

As a total-correctness machine-code Hoare triple:

$$|- \text{SPEC ARM\_MODEL}$$
$$\quad (\text{aR 0w x } \ast \text{ aPC p})$$
$$\{(p,0x\text{E0800000w})\}$$
$$\quad (\text{aR 0w (x+x) } \ast \text{ aPC (p+4w)})$$
Hoare triple

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

\[- (\text{ARM\_READ\_MEM} ((31 >> 2) (\text{ARM\_READ\_REG} 15w \text{ state})) \text{ state} = 0xE0800000w) \land \neg\text{state. undefined} \Rightarrow \\
(\text{NEXT\_ARM\_MMU} \text{ cp state} = \\
\quad \text{ARM\_WRITE\_REG} 15w (\text{ARM\_READ\_REG} 15w \text{ state} + 4w) \\
\quad (\text{ARM\_WRITE\_REG} 0w \\
\quad \quad (\text{ARM\_READ\_REG} 0w \text{ state} + \text{ARM\_READ\_REG} 0w \text{ state}) \text{ state})) \]

As a total-correctness machine-code Hoare triple:

\[- \text{SPEC ARM\_MODEL} \quad \text{Informal syntax for this talk:} \\
\quad (\text{aR} 0w x \ast \text{aPC} p) \quad \{ \text{R0} x \ast \text{PC} p \} \\
\quad \{(p,0xE08000000w)\} \quad p : E08000000 \\
\quad (\text{aR} 0w (x+x) \ast \text{aPC} (p+4w)) \quad \{ \text{R0} (x+x) \ast \text{PC} (p+4) \} \]
Demo.
Decompile

Decompiler automates Hoare triple reasoning.

**Example:** Given some ARM machine code,

0: E3A00000
4: E3510000
8: 12800001
12: 15911000
16: 1AFFFFFFB
Decompile

Decompiler automates Hoare triple reasoning.

**Example:** Given some ARM machine code,

<table>
<thead>
<tr>
<th>Address</th>
<th>Machine Code</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:</td>
<td>E3A00000</td>
<td>mov r0, #0</td>
</tr>
<tr>
<td>4:</td>
<td>E3510000</td>
<td>L: cmp r1, #0</td>
</tr>
<tr>
<td>8:</td>
<td>12800001</td>
<td>addne r0, r0, #1</td>
</tr>
<tr>
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<td>ldrne r1, [r1]</td>
</tr>
<tr>
<td>16:</td>
<td>1AFFFFFFFB</td>
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Decomposition

Decompiler automates Hoare triple reasoning.

Example: Given some ARM machine code,

\[
\begin{align*}
0: & \text{E3A00000 mov r0, #0} \\
4: & \text{E3510000 L: cmp r1, #0} \\
8: & \text{12800001 addne r0, r0, #1} \\
12: & \text{15911000 ldrne r1, [r1]} \\
16: & \text{1AFFFFFFF bne L}
\end{align*}
\]

the decompiler automatically extracts a readable function:

\[
\begin{align*}
f(r_0, r_1, m) &= \text{let } r_0 = 0 \text{ in } g(r_0, r_1, m) \\
g(r_0, r_1, m) &= \text{if } r_1 = 0 \text{ then } (r_0, r_1, m) \text{ else } \\
&\quad \text{let } r_0 = r_0 + 1 \text{ in } \\
&\quad \text{let } r_1 = m(r_1) \text{ in } \\
&\quad g(r_0, r_1, m)
\end{align*}
\]
Decompiler automatically proves a certificate theorem:

\[ f_{\text{pre}}(r_0, r_1, m) \Rightarrow \]
\[ \{ (R0, R1, M) \text{ is } (r_0, r_1, m) \ast \text{PC } p \ast S \} \]
\[ p : \text{E3A00000 E3510000 12800001 15911000 1AFFFFFFB} \]
\[ \{ (R0, R1, M) \text{ is } f(r_0, r_1, m) \ast \text{PC } (p + 20) \ast S \} \]

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 $f$,

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

since properties of $f$ carry over to machine code via the certificate.
Decomposition, verification example

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**Proof reuse**: Given similar x86 and PowerPC code:

31C085F67405408B36EBF7
38A000002C140000408200107E80A02E38A500014BFF0

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

\[ \text{tailrec}(x) = \text{if } G(x) \text{ then } \text{tailrec}(F(x)) \text{ else } D(x) \]
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

- compiler
- decompiler
- machine-code Hoare triple

- func
- code
- (code, thm)
- (func, thm)
- ARM
- x86
- PowerPC
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
2AFFFFFFFC  bcs L
```
Compiler

Synthesis often more practical. Given function $f$,

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our compiler generates ARM machine code:

```
E351000A L: cmp r1,#10
2241100A subcs r1,r1,#10
2AFFFFFFC bcs L
```

and automatically proves a certificate HOL theorem:

$$\vdash \{ R1 \ r_1 \ast PC \ p \ast s \}$$

$$p : E351000A \ 2241100A \ 2AFFFFFFC$$

$$\{ R1 \ f(r_1) \ast PC \ (p+12) \ast s \}$$
One can prove properties of \( f \) since it lives inside HOL:

\[ \forall x. f(x) = x \mod 10 \]
Compilation example, cont.

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

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

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

$$\vdash \{ R1 \ r_1 \times \text{PC} \ p \times s \}$$

\[ p : \text{E351000A 2241100A 2AFFFFFFC} \]

$$\{ R1 \ (r_1 \mod 10) \times \text{PC} \ (p+12) \times s \}$$
Compilation example, cont.

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

\[ \forall x. \ f(x) = x \mod 10 \]

Properties proved of \( f \) translate to properties of the machine code:

\[ \{ R1 \ r_1 \times PC \ p \times s \} \]

\[ p : \text{E351000A 2241100A 2AFFFFFFC} \]

\[ \{ R1 (r_1 \mod 10) \times PC (p+12) \times s \} \]

Additional feature: the compiler can use the above theorem to extend its input language with: let \( r_1 = r_1 \mod 10 \) in
Using our theorem about $\text{mod}$, the compiler accepts:

$$g(r_1, r_2, r_3) = \text{let } r_1 = r_1 + r_2 \text{ in}$$
$$\quad \text{let } r_1 = r_1 + r_3 \text{ in}$$
$$\quad \text{let } r_1 = r_1 \text{ mod } 10 \text{ in}$$
$$\quad (r_1, r_2, r_3)$$

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;
3. prove $f = f'$.

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]
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Demo.
LISP case study

Verified LISP implementations via compilation.

![Diagram](attachment://diagram.png)
LISP case study

Verified LISP implementations via compilation.

verified code for LISP primitives car, cdr, cons, etc.

compiler

decompiler

machine-code Hoare triple

ARM  x86  PowerPC
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HOL4 functions for LISP parse, eval, print

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ARM x86 PowerPC
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compiler

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machine-code Hoare triple

ARM, x86, PowerPC code and certificate theorems

ARM, x86, PowerPC
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
3. its semantics is deterministic.
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1. jumps are to fixed offsets or procedure returns,
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3. its semantics is deterministic.

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 || 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.

\[
\text{code} \xrightarrow{\text{decompiler}} (\text{func, thm})
\]
Talk summary

Decompilation:

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

Questions?

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