

Machine-code verification for multiple architectures

— An application of decompilation into logic

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Motivation

Formal verification of machine code:

machine code

code

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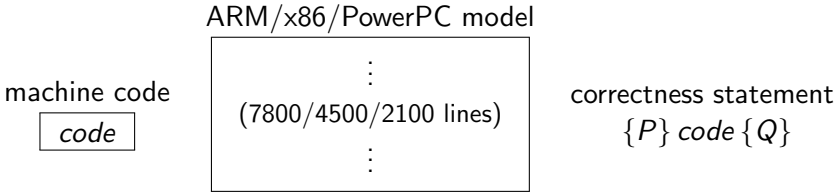
$code$

correctness statement

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

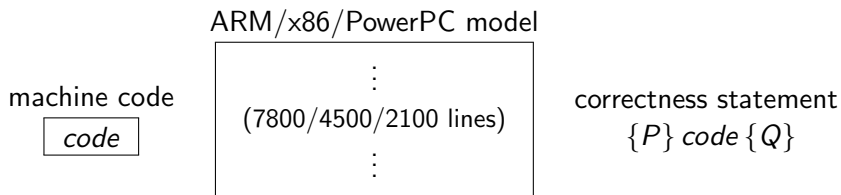
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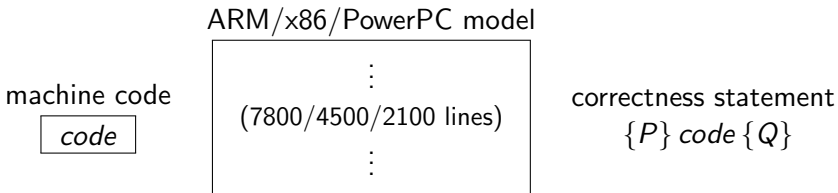


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Decompiler — extracts (with proof in HOL4) a function describing the effect of the code on the model.

Talk outline

1. what is decompilation into logic?
2. how to implement decompilation?

Basic idea

Example: Given some hard-to-read (ARM) machine code,

```
0: E3A00000
4: E3510000
8: 12800001
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0: E3A00000      mov r0, #0
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The decompiler produces a readable HOL4 function:

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

Decompilation, correct?

Decompiler automatically proves a certificate, which states that f describes the effect of the ARM code:

$$f_{pre}(r_0, r_1, m) \Rightarrow$$

$$\{ (R0, R1, M) \text{ is } (r_0, r_1, m) * \text{PC } p * S \}$$

$$p : \text{E3A00000 E3510000 12800001 15911000 1AFFFFF B}$$

$$\{ (R0, R1, M) \text{ is } f(r_0, r_1, m) * \text{PC } (p + 20) * S \}$$

Read informally as:

if initially reg 0, reg 1 and memory described by (r_0, r_1, m) , then the code terminates with reg 0, reg 1 and memory as $f(r_0, r_1, m)$

Decompilation, example

Precondition f_{pre} keeps track of side-conditions:

$$f_pre(r_0, r_1, m) = \text{let } r_0 = 0 \text{ in } g_pre(r_0, r_1, m)$$

$$g_pre(r_0, r_1, m) = \text{if } r_1 = 0 \text{ then } \mathit{true} \text{ else}$$
$$\quad \text{let } r_0 = r_0 + 1 \text{ in}$$
$$\quad \text{let } \mathit{cond} = r_1 \in \text{domain } m \wedge \mathit{aligned}(r_1) \text{ in}$$
$$\quad \text{let } r_1 = m(r_1) \text{ in}$$
$$\quad \quad g_pre(r_0, r_1, m) \wedge \mathit{cond}$$

Decompilation, verification example

Decompiler automatically produced: f , f_{pre} and certificate.

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To verify functional correctness, formalise “linked-list in memory”:

$$list(nil, a, m) = a = 0$$

$$list(cons\ x\ l, a, m) = \exists a'. m(a) = a' \wedge m(a+4) = x \wedge a \neq 0 \wedge list(l, a', m) \wedge aligned(a)$$

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Manual part of verification proof (14 lines in HOL4):

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

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

Decompilation, verification example, cont.

Using the automatically proved certificate:

$$f_{pre}(r_0, r_1, m) \Rightarrow$$

$$\{ (R0, R1, M) \text{ is } (r_0, r_1, m) * \text{PC } p * S \}$$

$$p : \text{E3A00000 E3510000 12800001 15911000 1AFFFFFFB}$$

$$\{ (R0, R1, M) \text{ is } f(r_0, r_1, m) * \text{PC } (p + 20) * S \}$$

Decompilation, verification example, cont.

Using the automatically proved certificate:

list(l, r₁, m) ⇒

{ (R0, R1, M) is (r₀, r₁, m) * PC p * S }

p : E3A00000 E3510000 12800001 15911000 1AFFFFFFB

{ (R0, R1, M) is (*length(l)*, 0, m) * PC (p + 20) * S }

Decompilation, proof reuse

x86	0:	31C0	xor eax, eax
	2:	85F6	L1: test esi, esi
	4:	7405	jz L2
	6:	40	inc eax
	7:	8B36	mov esi, [esi]
	9:	EBF7	jmp L1

L2:

PowerPC	0:	38A00000	addi 5,0,0
	4:	2C140000	L1: cmpwi 20,0
	8:	40820010	bc 4,2,L2
	12:	7E80A02E	lwzx 20,0(20)
	16:	38A50001	addi 5,5,1
	20:	4BFFFFFF0	b L1

L2:

Decompilation, proof reuse, cont.

Decompilation of x86 and PowerPC code:

$$f'(eax, esi, m) = \text{let } eax = eax \otimes eax \text{ in } g'(eax, esi, m)$$

$$g'(eax, esi, m) = \text{if } esi \& esi = 0 \text{ then } (eax, esi, m) \text{ else} \\ \text{let } eax = eax + 1 \text{ in} \\ \text{let } esi = m(es_i) \text{ in} \\ g'(eax, esi, m)$$

$$f''(r_5, r_{20}, m) = \text{let } r_5 = 0 \text{ in } g''(r_5, r_{20}, m)$$

$$g''(r_5, r_{20}, m) = \text{if } r_{20} = 0 \text{ then } (r_5, r_{20}, m) \text{ else} \\ \text{let } r_{20} = m(r_{20}) \text{ in} \\ \text{let } r_5 = r_5 + 1 \text{ in} \\ g''(r_5, r_{20}, m)$$

But in this case, easy to prove $f = f' = f''$ (3 lines in HOL4).

Decompilation, in a nut shell

Proof-producing decompilation:

- ▶ takes machine code, returns function and certificate
- ▶ keeps manual proofs independent of underlying model
(possible proof reuse)

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2. how to implement decompilation?
 - ▶ processor models
 - ▶ machine-code specifications: “{...} *code* {...}”
 - ▶ tail-recursive functions

ISA models

Underlying ISA specifications:

ARM – developed by Anthony Fox, verified against a register-transfer level model of an ARM processor;

x86 – developed together with Susmit Sarkar, Peter Sewell, Scott Owens, etc, heavily tested against a real processor;

PowerPC – a HOL4 translation of Xavier Leroy's PowerPC model, used in his proof of an optimising C compiler.

Large detailed models...

Machine code, x86

Even 'simple' instructions get complex definition.

Sequential op.sem. evaluated for instruction "40" (i.e. `inc eax`):

```
x86_read_reg EAX state = eax ∧  
x86_read_eip state = eip ∧  
x86_read_mem eip state = some 0x40 ⇒  
x86_next state =  
  some (x86_write_reg EAX (eax + 1)  
    (x86_write_eip (eip + 1)  
      (x86_write_eflag AF none  
        (x86_write_eflag SF (some (sign_of(eax + 1)))  
          (x86_write_eflag ZF (some (eax + 1 = 0))  
            (x86_write_eflag PF (some (parity_of(eax + 1)))  
              (x86_write_eflag OF none state))))))))))
```


Machine code, specifications

A machine-code specifications:

$$\{ R \text{ EAX } a * \text{ EIP } p * S \}$$

$$p : 40$$

$$\{ R \text{ EAX } (a+1) * \text{ EIP } (p+1) * S \}$$

where S existentially quantifies the status flags:

$$S = \exists a s z p o. \text{ eflag AF } a * \text{ eflag SF } s * \text{ eflag ZF } z * \dots$$

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$$\forall P. \{ R \text{ EAX } a * \text{ EIP } p * S * P \}$$
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$$\{ R \text{ EAX } a * \text{ EIP } p * S * R \text{ EBX } b \}$$

$$p : 01D8$$

$$\{ R \text{ EAX } (a+b) * \text{ EIP } (p+2) * S * R \text{ EBX } b \}$$

where S existentially quantifies the status flags:

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$$\{ R \text{ EAX } (a+1) * \text{ EIP } (p+1) * S * R \text{ EBX } b \}$$

$$p+1 : 01D8$$

$$\{ R \text{ EAX } (a+1+b) * \text{ EIP } (p+3) * S * R \text{ EBX } b \}$$

where S existentially quantifies the status flags:

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Machine code, specifications

A machine-code specifications:

$$\{ R \text{ EAX } a * \text{ EIP } p * S * R \text{ EBX } b \}$$
$$p : 4001D8$$
$$\{ R \text{ EAX } (a+1+b) * \text{ EIP } (p+3) * S * R \text{ EBX } b \}$$

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Tail-recursive functions

How to implement the proof-producing translation?

Key ideas:

1. define functions as instances of

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

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$$\textit{pre}(x) = \exists n. \neg(G(F^n(x))) \wedge (\forall x. \dots \Rightarrow H(x))$$

3. but give the user

$$\textit{pre}(x) = (\text{if } G(x) \text{ then } \textit{pre}(F(x)) \text{ else true}) \wedge H(x)$$

4. actually also insert side-condition $H(x)$

Tail-recursive functions, cont.

5. use the following loop rule, one loop at a time:

$\forall P Q.$

$$(\forall x. H(x) \wedge G(x) \Rightarrow \{P(x)\} \text{ code } \{P(F(x))\}) \Rightarrow$$

$$(\forall x. H(x) \wedge \neg G(x) \Rightarrow \{P(x)\} \text{ code } \{Q(D(x))\}) \Rightarrow$$

$$(\forall x. \text{pre}(x) \Rightarrow \{P(x)\} \text{ code } \{Q(\text{tailrec}(x))\})$$

Decompilation algorithm

Algorithm:

1. derive specifications for individual instructions;
2. find control flow;
3. compose specifications;
4. apply loop rule;
5. exit or go to step 3.

Details in paper...

Decompilation, restrictions

Restrictions:

1. **heuristics used for control-flow discovery**, cannot handle code-pointers (except subroutine call/return).
2. **underlying ISA model must be deterministic** (at least for the code which is decompiled).

Robust: heuristics only used for control-flow discovery.

Applications

Verification case studies done:

- ▶ copying garbage collectors, LISP primitives (car, cdr, cons, ...)

Used in proof-producing compiler:

- ▶ compiles HOL4 functions to ARM, x86, PowerPC code;
- ▶ compiler used to produce verified LISP interpreters.

Other applications?

- ▶ link to your favorite tool? (no need to trust C compiler...)

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Questions?