An executable semantics for CompCert

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Introduction

In the CerCo project we've been working on

> *the construction of a formally verified complexity preserving compiler from a large subset of C to some typical microcontroller assembly*

Inspired by (and borrowing a little from) Leroy et al's CompCert.

They define languages by small-step inductive definitions.
We define language with executable interpreters.

Executable semantics are easier to test.

Can we retrofit executable semantics to CompCert and find out anything interesting?

C is quirky, flawed, and an enormous success.

— dmr, HOPL'93.

What's so difficult about C?

Around 160 A4 pages of specification (400 with libraries added).

Implicit conversions:

```
int x = 'a' + 0.5;
```

Mixed reads and writes of an object are undefined:

```
x = i + i++;
```

Evaluation order constraints very lax, not uniform:

```
x = i++ && i++;
x = i++ & i++;
```

Annoying corner cases:

```
int x[];
int main() { return x[0]; }
```

CompCert History (up to 1.8 — a.k.a. V4)

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  - `goto`s, and ...

The latter comes in two flavours:

1. A non-deterministic version (the intended input language)
2. A deterministic version (what the compiler actually does)

CompCert and testing

Untrustworthy OCaml Formal development in Coq

C $\to$ CompCert C $\to$ Clight $\longrightarrow$ ASM $\to$ Machine code

Coq sections get ‘extracted’ to OCaml for execution.

There’s a formal proof in the middle,
but the edges are a bit worrying.

CompCert and testing

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Normal testing tries all of the code.

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CompCert C $\to$ Clight $\longrightarrow$ ASM

Proofs exercise the formal development.

- Tactical interactive theorem proving helps you notice bad definitions

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C $\rightarrow$ CompCert C

With an executable semantics we can test the first part.

- Holes in the specification can mask holes in the proof
- Can also detect undefined behaviour in C programs

Constructing the executable semantics

CompCert provides us with a head start:

- the memory model is executable,
- local and global environments are defined in terms of functions,
- the semantics of operators such as $+$, $==$, etc are defined by functions,
- an error monad is available for failing.

In particular, environments are used by the compiler, so they are also fairly efficient.

Constructing the executable semantics

Syntax directed relations are easy to make functions from:

```
Inductive lred: expr -> mem -> expr -> mem -> Prop :=
  | red_var_local: forall x ty m b,
      e!x = Some(b, ty) ->
      lred (Evar x ty) m
           (Eloc b Int.zero ty) m
...
```

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Definition exec_lred (e:expr) (m:mem) : res (expr * mem) :=
match e with
| Evar x ty =>
    match en!x with
    | Some (b, ty') => match type_eq ty ty' with
                       | left _ => OK (Eloc b Int.zero ty, m)
                       | right _ => Error (msg "type mismatch")
                       end
...
```

Constructing the executable semantics — non-determinism

$$e \to e' \quad \Rightarrow \quad C[e] \to C[e']$$

Non-determinism appears as the choice of redex and context.

We encode execution strategies as functions

```
expr -> kind * expr * (expr -> expr)
```

and require that it really does give a subexpression and context.

Doesn't cover all strategies:

- Implementations could use contextual information, randomness. . .
- various methods can solve this, but not terribly important here

Constructing the executable semantics — stuck subexpressions

The non-deterministic semantics check for stuck subexpressions.

- picks up non-terminating programs with undefined behaviour
- example where `f` does not terminate:

```
f() + (10 / x)      with x = 0
```

- should be able to get stuck after substituting `x`
- but without check we can always reduce `f()`

Naïve implementation would be inefficient:

> *any subexpression in an evaluation context is either a value, or has a further subexpression that is reducible*

but there is a nice structurally recursive version.

Soundness and completeness

We want to know that the executable semantics does the same thing as the original semantics.

- (mostly boring) inductive proofs
- Coq's `Function` feature for generating induction principles tailored to particular functions is great, but still a bit limited

Caveats apply to completeness:

- Limitations on strategies — cheat by single-stepping
- No I/O (CerCo uses a resumption monad for I/O.)

Strategies and the deterministic semantics

Two variants have been implemented:

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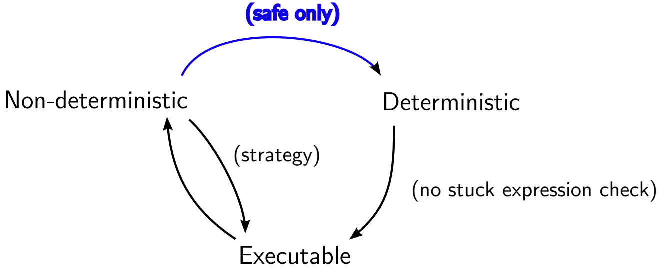

Completeness proof interesting:

- Deterministic semantics has big-step for 'simple' expressions
- Proof shows that this really does correspond to non-deterministic

OCaml driver code

Complete the interpreter with some untrustworthy OCaml:

1. Repeat the Coq step function until the program stops or fails.
2. Add optional code to work around bugs
   - don't need to fix them properly
   - don't need to prove anything
3. Also good for hacks: `memcpy`, `printf`, ...
   Implement things outside of CompCert's model of C.

Testing — function pointers

The example that I originally wanted to try.

```
int zero(void) { return 0; }

int main(void) {
  int (*f)(void) = zero;
  return f();
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```
$ ../compcert-git-badfn/cexec fnptr-simple.c
stuck expression:  function value hasn't a function type
```

The function call rule requires `f` to evaluate directly to a function, not a pointer.

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  return f();
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```

Fixing this is easy — the compiler already had the correct type check!

And the proof scripts got shorter.

Testing — Csmith

Random program generator by Yang et al from U. Utah.

- Targets ‘middle-end’ bugs
- Regular testing only found bugs in untrustworthy OCaml code
- Random code didn’t find any errors in semantics

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Testing — Csmith

...but the non-random code of safe mathematics functions...

```
int8_t lshift_func_int8_t_s_s(int8_t left, int right)
{
  return
    ((left < 0) ||
     (((int)right) < 0) ||
     (((int)right) >= 32) ||
     (left > (INT8_MAX >> ((int)right)))) ?

    left :

    (left << ((int)right));
}
```

Semantics is missing arithmetic conversion for `?:`.

But the compiler works on this example, because 'all' integers are 32 bits.

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```
double f(int x, int a, double b) {
  return x ? a : b;
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```
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The compiler is missing the conversion too:

```
$ ../compcert-git/ccomp conditional.c
Error during RTL type inference:  type mismatch
In function main:  RTL type inference error
```

We made a failing test-case from a working one.

Testing — `gcc-torture`

An executable subset of GCC's C test suite, pre-filtered by another executable semantics project (kcc from U. Illinois).
Lots of fun:

- lack of initialisation
  1. only in the semantics, and
  2. not in the compiler in OCaml
- a little array/pointer confusion (OCaml)
- incomplete array type mismatches (both, kind of)
- Missing trivial cases for cast (semantics, fixed already)
- pointer comparisons (semantics, intentional limitation)
- bad line numbers in errors (OCaml)
  - not helped by OCaml's non-deterministic evaluation order...

Related work

CompCert response

- bugs fixed, sometimes before I found them
- fresh interpreter implementation
  - ⋆ inspired by this work, but different: finds all possible redexes, turns out smaller and neater; doesn't explicitly do deterministic semantics

Lots of other executable semantics exist

- kcc, CompCertTSO, some JVMs, . . .
- often the natural way to use a system (e.g., ACL2)
  Milner and Weyhrauch 1972

More fun things you can do

- Add I/O, full program evaluation
- Check for coverage

Conclusions

Took an existing verified compiler,

- added an executable version of the semantics,
- found bugs through testing,
  - including a bug in the formalized front-end
  - even though the original test-case is compiled properly
- useful for illustrating limitations of the semantics, especially ones you didn't know about,
- showed that the semantics cope with a large group of tests,
- showed a connection between the original deterministic and non-deterministic semantics.

`http://homepages.inf.ed.ac.uk/bcampbe2/compcert/`