CerCo Work Package 4

Dominic Mulligan
Postdoc, University of Bologna

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Overview of progress

Status at end of first period:

Executable semantics of MCS-51 in OCaml and Matita

Goals for the end of second period:

Executable semantics of back-end intermediate languages

Encoding of compiler back-end in CIC

Contents

Outline

SEVENTH FRAMEWORK PROGRAMME

Backend intermediate languages

RTLabs
- ↓ copy propagation ×
- ↓ instruction selection ✓
- ↓ change of memory models in compiler ✓

RTL
- ↓ constant propagation ×
- ↓ calling convention made explicit ✓
- ↓ layout of activation records ✓

ERTL
- ↓ register allocation and spilling ✓
- ↓ dead code elimination ✓

LTL
- ↓ function linearisation ✓
- ↓ branch compression ×

LIN
- ↓ relabeling ✓

ASM

Joint: a new approach I

- Consecutive languages in backend must be similar
- Transformations between languages translate away some small specific set of features
- But looking at OCaml code, not clear precisely what differences between languages are, as code is repeated
- Not clear if translation passes can commute, for instance
- CerCo passes are in a different order to CompCert (calling convention and register allocation done in different places)
- Instruction selection done early: changing subset of instructions used would require instructions to be duplicated everywhere in backend

`Joint`: a new approach II

- Idea: all of these languages are just instances of a single language
- This language `Joint` is parameterised by a type of registers to be used in instructions, and so forth
- Each language after RTLabs is now just defined as the `Joint` language instantiated with some concrete types
- Similarly for semantics: common definitions that take e.g. type representing program counters as parameters

Joint: a new approach III

Joint instructions allow us to embed language-specific instructions:

```
inductive joint_instruction (p: params__) (globals: list ident): Type[0] :=
 | COMMENT: String → joint_instruction p globals
 | COST_LABEL: costlabel → joint_instruction p globals
 ...
 | COND: acc_a_reg p → label → joint_instruction p globals
 | extension: extend_statements p → joint_instruction p globals.

inductive ertl_statement_extension: Type[0] :=
 | ertl_st_ext_new_frame: ertl_statement_extension
 | ertl_st_ext_del_frame: ertl_statement_extension
 | ertl_st_ext_frame_size: register → ertl_statement_extension.
```

Joint: a new approach IV

- Languages that provide extensions need to provide translations and semantics for those extensions
- Everything else can be handled at the Joint-level
- This modularises the handling of these languages

`Joint`: advantages I

- We can recover the concrete OCaml languages by instantiating parameterized types
- Why use `Joint`?
- Reduces repeated code (fewer bugs, or places to change)
- Unify some proofs, making correctness proof easier
- Generic optimizations (e.g. constant propagation)

`Joint`: advantages II

- Easier to add new intermediate languages as needed
- Easier to see relationship between consecutive languages at a glance
- MCS-51 instruction set embedded in `Joint` syntax
- Simplifies instruction selection
- We can investigate which translation passes commute much more easily

Semantics of `Joint` I

- As mentioned, use of `Joint` also unifies semantics of these languages
- We use several sets of records, which represent the state that a program is in
- These records are parametric in representations for e.g. frames

A new intermediate language

- Matita backend includes a new intermediate language: RTLntc
- Sits between RTL and ERTL
- RTLntc is the RTL language where all tailcalls have been eliminated
- This language is 'implicit' in the OCaml compiler
- There, the RTL to ERTL transformation eliminates tailcalls as part of translation
- But including an extra, explicit intermediate language is 'almost free' using the `Joint` language approach

The LTL to LIN transform I

- `Joint` clearly separates fetching from program execution
- We can vary how one works whilst fixing the other
- Linearisation is moving from fetching from a graph-based language to fetching from a list-based program representation
- The order of transformations in OCaml prototype is fixed
- Linearisation takes place at a fixed place, in the translation between LTL and LIN
- The Matita compiler is different: linearisation is a generic process
- Any graph-based language can now be linearised

The LTL to LIN transform II

- CompCert backend linearises much sooner than CerCo's
- Can now experiment with linearising much earlier
- Many transformations and optimisations can work fine on a linearised form
- Only place in the (current) backend that requires a graph-based language is in the ERTL pass, where we do a dataflow analysis

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Outline

Time not reported

- We had six months of time which is not reported on in any deliverable
- We invested this time working on:
  - The global proof sketch
  - The setup of 'proof infrastructure', common definitions, lemmas, invariants etc. required for main body of proof
  - The proof of correctness for the assembler
  - A notion of 'structured traces', used throughout the compiler formalisation, as a means of eventually proving that the compiler correctly preserves costs
  - Structured traces were defined in collaboration with the team at UEDIN

Assembler

- After LIN, compiler spits out assembly language for MCS-51
- Assembler has pseudoinstructions similar to many commercial assembly languages
- For instance, instead of computed jumps (e.g. `SJMP` to a specific address), compiler can simply spit out a generic jump instruction to a label
- Simplifies the compiler, at the expense of introducing more proof obligations
- Now need a formalized assembler (a step further than CompCert)

A problem: jump expansion

- 'Jump expansion' is our name for the standard 'branch displacement' problem
- Given a pseudojump to a label *l*, how best can this be expanded into an assembly instruction `SJMP`, `AJMP` or `LJMP` to a concrete address?
- Problem also applies to conditional jumps
- Problem especially relevant for MCS-51 as it has a small code memory, therefore aggressive expansion of jumps into smallest possible concrete jump instruction needed
- But a known hard problem (NP-complete depending on architecture), and easy to imagine knotty configurations where size of jumps are interdependent

Jump expansion I

- We employed the following tactic: split the decision over how any particular pseudoinstruction is expanded from pseudoinstruction expansion
- Call the decision maker a 'policy'
- We started the proof of correctness for the assembler based on the premise that a correct policy exists
- Further, we know that the assembler only fails to assemble a program if a good policy does not exist (a side-effect of using dependent types)
- A bad policy is a function that expands a given pseudojump into a concrete jump instruction that is 'too small' for the distance to be jumped, or makes the program consume too much memory

Jump expansion II

- Jaap Boender at UNIBO has been working on a verified implementation of a good jump expansion policy for the MCS-51
- The strategy initially translates all pseudojumps as `SJMP` and then increases their size if necessary
- Termination of the procedure is proved, as well as a safety property, stating that jumps are not expanded into jumps that are too long
- His strategy is not optimal (though the computed solution is optimal for the strategy employed)
- Jaap's work is the first formal treatment of the 'jump expansion problem'

Assembler correctness proof

- Assuming the existence of a good jump expansion property, we completed about 75% of the correctness proof for the assembler
- Jaap's work has just been completed (modulo a few missing lemmas)
- Postponed the remainder of main assembler proof to start work on other tasks (and for Jaap to finish)
- We intend to return to proof, and publish an account of the work (possibly) as a journal paper

Outline

Who pays? I

In C:

```
int main(int argc, char** argv) {
  cost_label1:
    ...
    some_function();
  cost_label2:
    ...
}
```

In ASM:

```
  ...
main:
  ...
cost_label1:
  ...
  LCALL some_function
cost_label2:
  ...
```

- Where do we put cost labels to capture execution costs?
- Proof obligations complicated by panoply of labels
- Doesn't work well with `g(h() + 2 + f())`
- Is `cost_label2` ever reached?
- `some_function()` may not return correctly

Who pays? II

- Solution: omit `cost_label2` and just keep `cost_label1`
- We pay for everything 'up front' when entering a function
- No need to prove `some_function()` terminates
- But now execution of functions in CerCo takes a particular form
- Functions begin with a label, call other functions that begin with a label, eventually return, but *return* to the correct place
- 'Recursive structure'

Structured traces I

- We introduced a notion of 'structured traces'
- These are intended to statically capture the (good) execution traces of a program
- To borrow a slogan: they are the 'computational content of a well-formed program's execution'
- Come in two variants: inductive and coinductive
- Inductive captures program execution traces that eventually halt, coinductive ones that diverge

Structured traces II

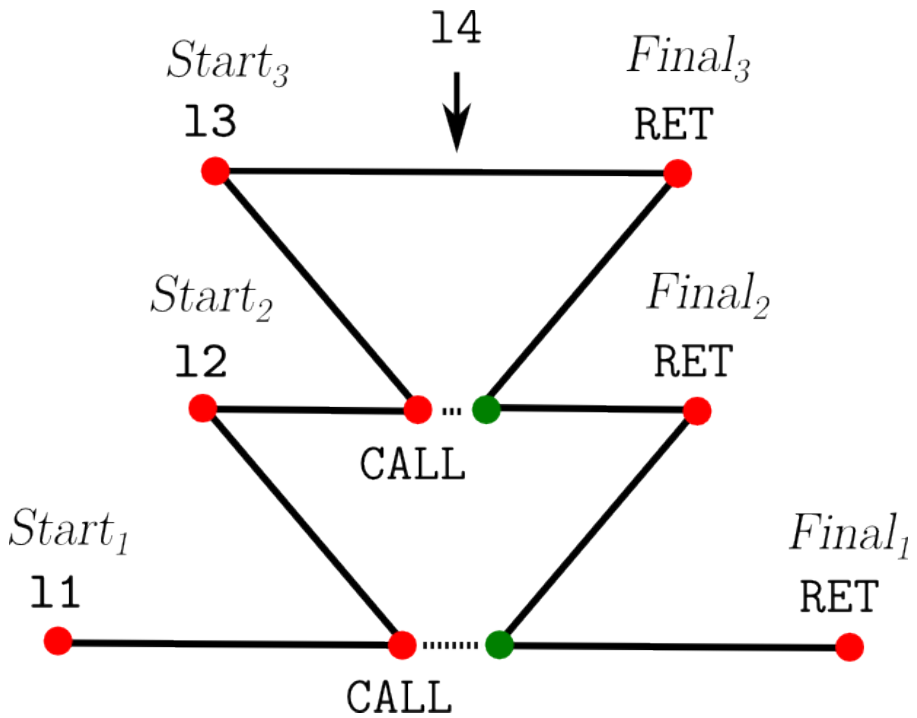
- I focus on the inductive variety, as used the most (for now) in the backend
- In particular, used in the proof that static and dynamic cost computations coincide
- Traces preserved by backend compilation, initially created at RTL
- This will be explained later

Structured traces III

- Central insight is that program execution is always in the body of some function (from `main` onwards)
- A well formed program must have labels appearing at certain spots
- Similarly, the final instruction executed when executing a function must be a `RET`
- Execution must then continue in body of calling function, at correct place
- These invariants, and others, are crystalised in the specific syntactic form of a structured trace

Recursive structure of 'good' execution I

- All calls return to the correct place
- `CALL`s and `JMP`s only to labels



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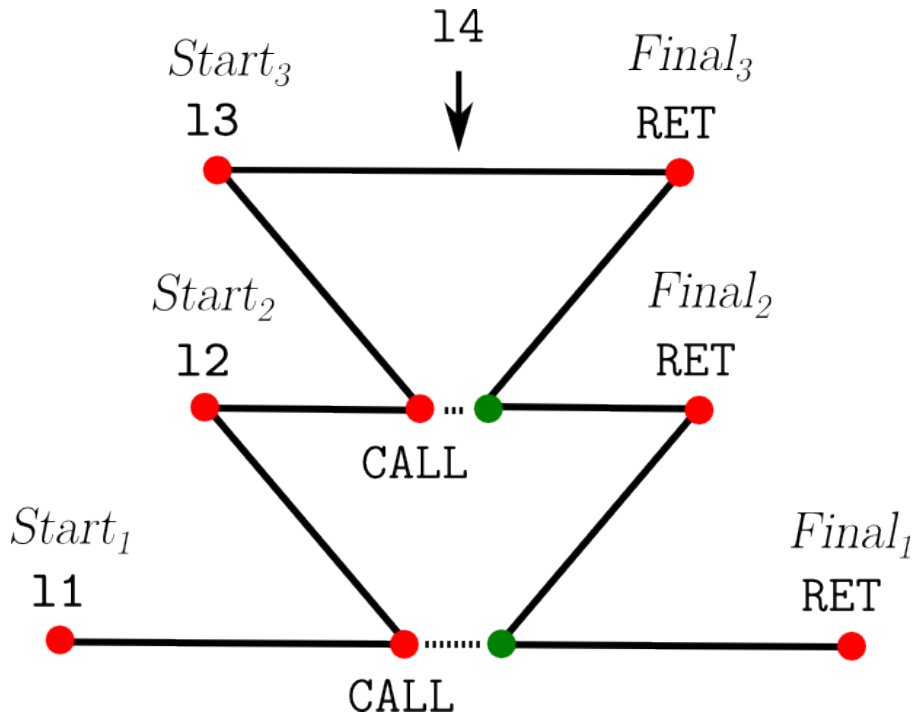
Static and dynamic costs




```
emit(I1)
MOV r1 0
ADD r1 r2
CALL f
ADD r2 r2
MOV r2 0
RET
```

$k(I_1) = k(\text{MOV}) + k(\text{ADD}) + \ldots + k(\text{RET})$

Static-cost(trace) $= k(I_1) + \ldots + k(I_4)$

Dynamic-cost(trace) $=$ clock(Final_1) - clock(Start_1)

Theorem: Static-cost(trace) $=$ Dynamic-cost(trace)

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Static and dynamic costs II

This proof is surprisingly tricky to complete ($\approx$ 3 man months)

- Issues
  - Finite memory
    the PC can overflow during fetching and/or execution
  - Variable length instructions
    not all addresses corresponds to instruction boundaries
- Requires predicates defining 'good program' and 'good program counter'
- Is now about 95% complete

Outline

Changes ported to OCaml prototype

- Bug fixes spotted in the formalisation so far have been merged back into the OCaml compiler
- Larger changes like the `Joint` machinery have so far not
- It is unclear whether they will be
- Just a generalisation of what is already there
- Supposed to make formalisation easier
- Further, we want to ensure that the untrusted compiler is as correct as possible, for experiments in e.g. Frama-C
- Porting a large change to the untrusted compiler would jeopardise these experiments

Improvements in Matita

- Part of the motivation for using Matita was for CerCo to act a 'stress test'
- The proofs talked about in this talk have done this
- Many improvements to Matita have been made since the last project meeting
- These include major speed-ups of e.g. printing large goals, bug fixes, the porting of CerCo code to standard library, and more options for passing to tactics

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The next period

UNIBO has following pool of remaining manpower (postdocs):

Person	Man months remaining
Boender	10 months
Mulligan	6 months
Tranquilli	10 months

- Boender finishing assembler correctness proof
- Mulligan proofs of correctness for 1 intermediate language
- Tranquilli proofs of correctness for 2 intermediate languages
- Sacerdoti Coen 'floating'
- Believe we have enough manpower to complete backend (required 21 man months)

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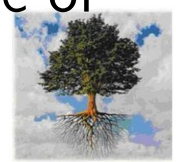
Summary

We have:

- Translated the OCaml prototype's backend intermediate languages into Matita
- Implemented the translations between languages, and given the intermediate languages a semantics
- Refactored many of the backend intermediate languages into a common, parametric 'joint' language, that is later specialised
- Spotted opportunities for possibly commuting backend translation passes
- Used six months to define structured traces and start the proof of correctness for the assembler
- Distinguished our proof from CompCert's by heavy use of dependent types throughout whole compiler



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