The CompCert verified C compiler

Compiler built and proved by Xavier Leroy et al.

Talk given by David Pichardie - Harvard University / INRIA Rennes

Slides largely inspired by Xavier Leroy own material

Critical embedded software

```
        .const
        .align  2
___stringlit_1:
        .ascii  "integr(square, 0.0, 1.0,
        .text
        .align  4
_square:
        subl    $12, %esp
        leal    16(%esp), %edx
        movl    %edx, 0(%esp)
        movl    0(%esp), %edx
        movsd   0(%edx), %xmm0
        mulsd   %xmm0, %xmm0
        subl    $8, %esp
        movsd   %xmm0, 0(%esp)
        fldl    0(%esp)
        addl    $8, %esp
        addl    $12, %esp
        ret
        .text
        .align  4
_integr:
        subl    $60, %esp
        leal    64(%esp), %edx
        movl    %edx, 8(%esp)
        movl    %ebx, 20(%esp)
        movl    %esi, 24(%esp)
        movl    8(%esp), %edx
        movl    0(%edx), %esi
        movl    8(%esp), %edx
        movsd   4(%edx), %xmm6
        movsd   %xmm6, 48(%esp)
        movl    8(%esp), %edx
        movsd   12(%edx), %xmm6
        movsd   %xmm6, 32(%esp)
        movl    8(%esp), %edx
        movl    20(%edx), %ebx
        movsd   32(%esp), %xmm6
        movsd   48(%esp), %xmm7
        subsd   %xmm7, %xmm6
        movsd   %xmm6, 32(%esp)
        cvtsi2sd %ebx, %xmm1
        movsd   32(%esp), %xmm6
        divsd   %xmm1, %xmm6
        movsd   %xmm6, 32(%esp)
        xorpd   %xmm6, %xmm6 # +0.0
        movsd   %xmm6, 40(%esp)
L100:
        cmpl    $0, %ebx
        jle     L101
        movsd   48(%esp), %xmm6
        movsd   %xmm6, 0(%esp)
        call    *%esi
        subl    $8, %esp
        fstpl   0(%esp)
        movsd   0(%esp), %xmm0
        addl    $8, %esp
        movsd   40(%esp), %xmm6
        addsd   %xmm0, %xmm6
        movsd   %xmm6, 40(%esp)
        leal    -1(%ebx), %ebx
        movsd   48(%esp), %xmm6
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        jmp     L100
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        movl    20(%esp), %ebx
        movl    24(%esp), %esi
        addl    $60, %esp
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        .text
        .align  4
        .globl _test
_test:
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        movl    %ebx, 36(%esp)
        movl    24(%esp), %edx
        movl    0(%edx), %eax
        leal    _square, %ebx
        xorpd   %xmm2, %xmm2 # +0.0
        movsd   L102, %xmm1 # 1
        movl    %ebx, 0(%esp)
        movsd   %xmm2, 4(%esp)
        movsd   %xmm1, 12(%esp)
        movl    %eax, 20(%esp)
        call    _integr
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L102:   .quad   0x3ff0000000000000
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        call    _printf
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critical_prog.ppc

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High degree of assurance is required

- is the program critical_prog.ppc safe ?

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        call    _printf
        xorl    %eax, %eax
        movl    28(%esp), %ebx
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        ret
```

critical_prog.ppc

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- is the program critical_prog.ppc safe ?

2 options:

- qualify the PPC program as if hand-written (intensive testing, painful manual review...)

- qualify the program at the source level (static analysis, model checking, or program proof)

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        .text
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        movl    8(%esp), %edx
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        movl    8(%esp), %edx
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        subsd   %xmm7, %xmm6
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        xorpd   %xmm6, %xmm6 # +0.0
        movsd   %xmm6, 40(%esp)
L100:
        cmpl    $0, %ebx
        jle     L101
        movsd   48(%esp), %xmm6
        movsd   %xmm6, 0(%esp)
        call    *%esi
        subl    $8, %esp
        fstpl   0(%esp)
        movsd   0(%esp), %xmm0
        addl    $8, %esp
        movsd   40(%esp), %xmm6
        addsd   %xmm0, %xmm6
        movsd   %xmm6, 40(%esp)
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        movsd   48(%esp), %xmm6
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        leal    ___stringlit_1, %eax
        movl    %eax, 0(%esp)
        movl    %ebx, 4(%esp)
        movsd   %xmm0, 8(%esp)
        call    _printf
        xorl    %eax, %eax
        movl    28(%esp), %ebx
        addl    $44, %esp
        ret
```

critical_prog.ppc

Critical embedded software

High degree of assurance is required

- is the program critical_prog.ppc safe ?

2 options:

- qualify the PPC program as if hand-written (intensive testing, painful manual review...)
- qualify the program at the source level (static analysis, model checking, or program proof)

2nd option is preferred in practice

- can you trust your compiler ?
- this talk: apply formal verification techniques to the compiler itself !

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critical_prog.ppc

Miscompilation happens

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NULLSTONE isolated defects [in integer division] in twelve of twenty commercially available compilers that were evaluated.

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We created a tool that generates random C programs, and then spent two and a half years using it to find compiler bugs. So far, we have reported more than 290 previously unknown bugs to compiler developers. Moreover, every compiler that we tested has been found to crash and also to silently generate wrong code when presented with valid inputs.

J. Regehr et al, 2010

How do we verify a compiler ?

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A simple idea:

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Program and prove your compiler in the same language !

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Which language ?

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Which language ?

Coq: an animal with two faces

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- a functional programming language with a very rich type system

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  example:

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sort: ∀ l: list int, { l': list int |
                          Sorted l' ∧ PermutationOf l l' }
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- with an extraction mechanism to Ocaml

```
sort: int list → int list
```

Verifying a compiler in Coq

A simple recipe

Logical Framework
(here Coq)

Verifying a compiler in Coq
A simple recipe

Program the compiler inside Coq

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Definition compiler
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State its correctness wrt. a formal specification of the language semantics

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Theorem compiler_is_correct :
  ∀ p, compiler p = Some p' →
       behaviors(p') ⊆ behaviors(p)
```

If compilation succeeds, the generated code should behave as prescribed by the semantics of the source program.

Compiler

Source & Target Language Semantics

Logical Framework
(here Coq)

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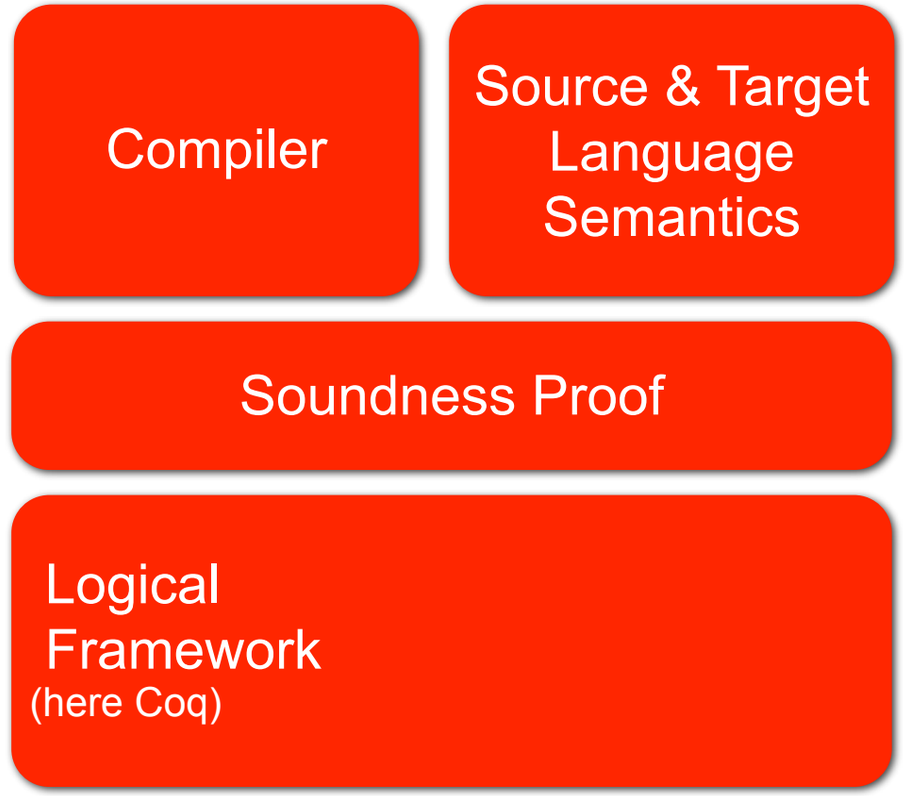
```

We interactively and mechanically prove this theorem

```
Proof. ... (* few days later *) ... Qed.
```



Verifying a compiler in Coq
A simple recipe

Program the compiler inside Coq

```
Definition compiler
  (p:source) : option target := ...
```

State its correctness wrt. a formal specification of the language semantics

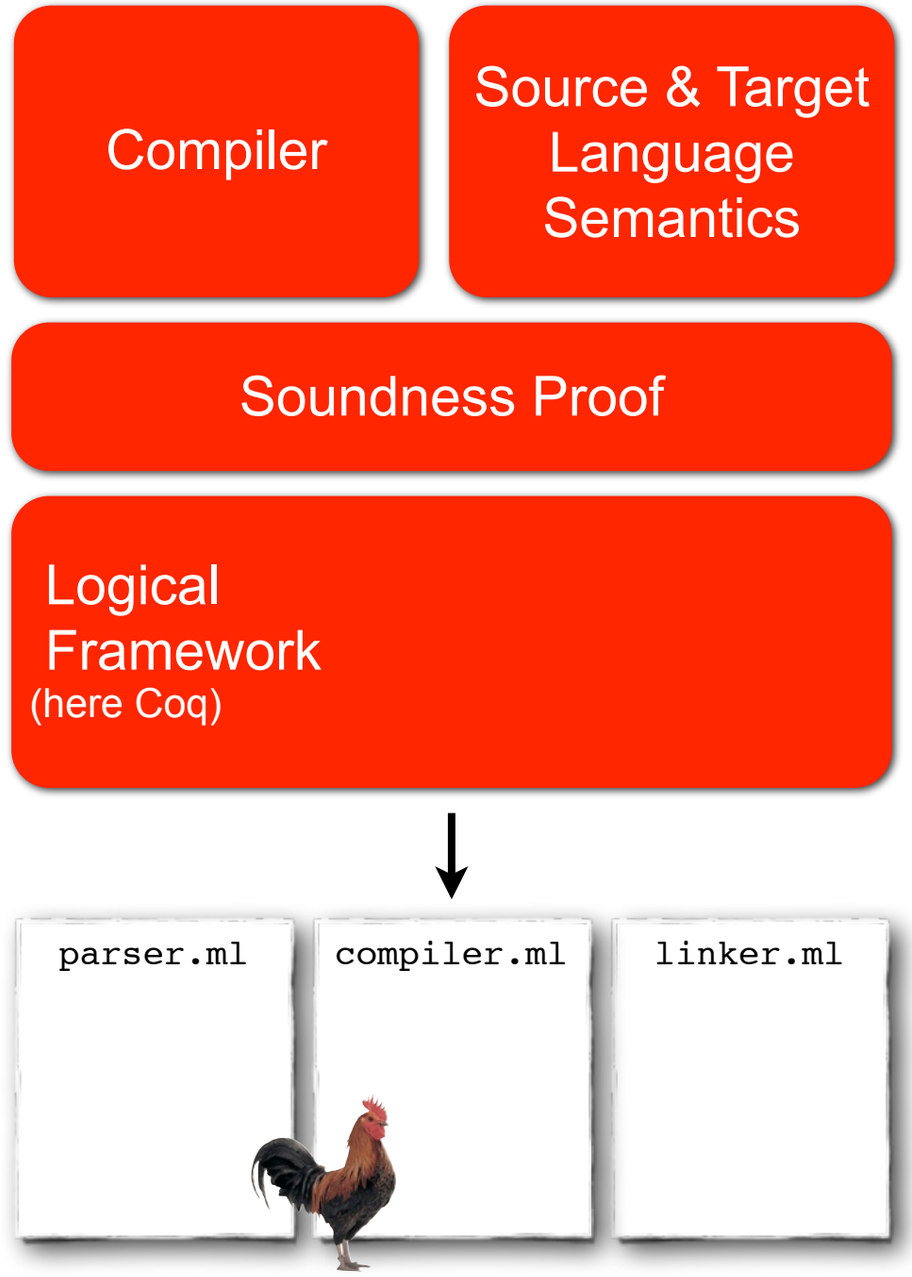
```
Theorem compiler_is_correct :
  ∀ p, compiler p = Some p' →
       behaviors(p') ⊆ behaviors(p)
```

We interactively and mechanically prove this theorem

```
Proof. ... (* few days later *) ... Qed.
```

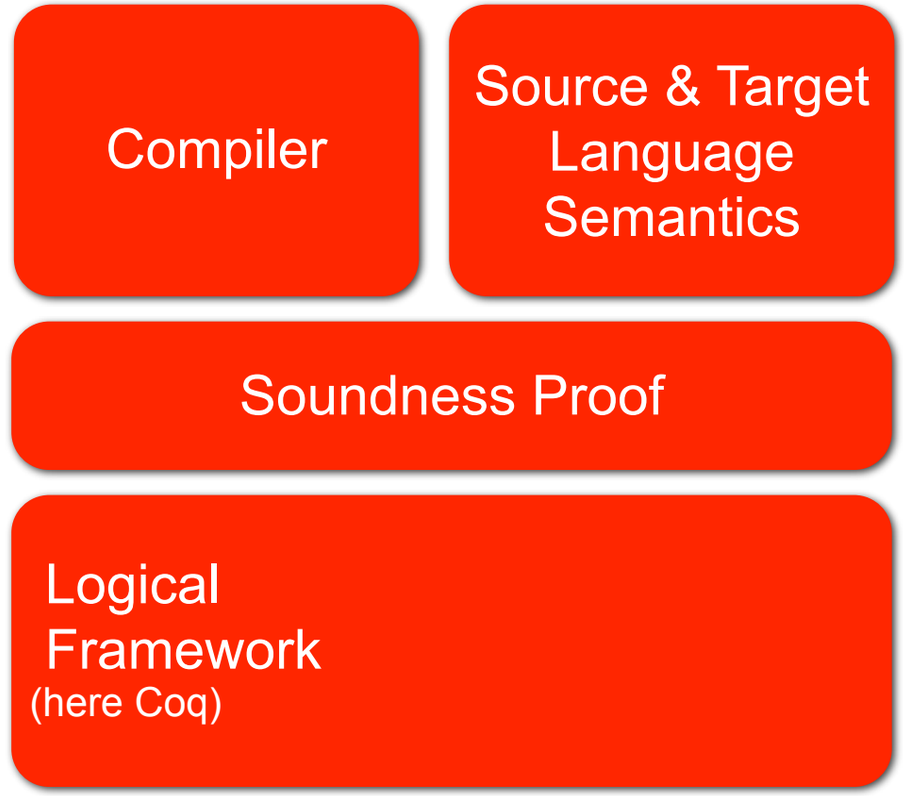
We extract an OCaml implementation of the compiler

```
Extraction compiler.
```



Trusted Computing Base (TCB)

1. Formal specification of the programming language semantics
   - already (informally) shared between any end-user programmer, compiler, static analyzer
   - must itself be rigorously proofread/animated/tested
2. Logical Framework
   - only the proof checker needs to be trusted
   - we don’t trust sophisticated decision procedures



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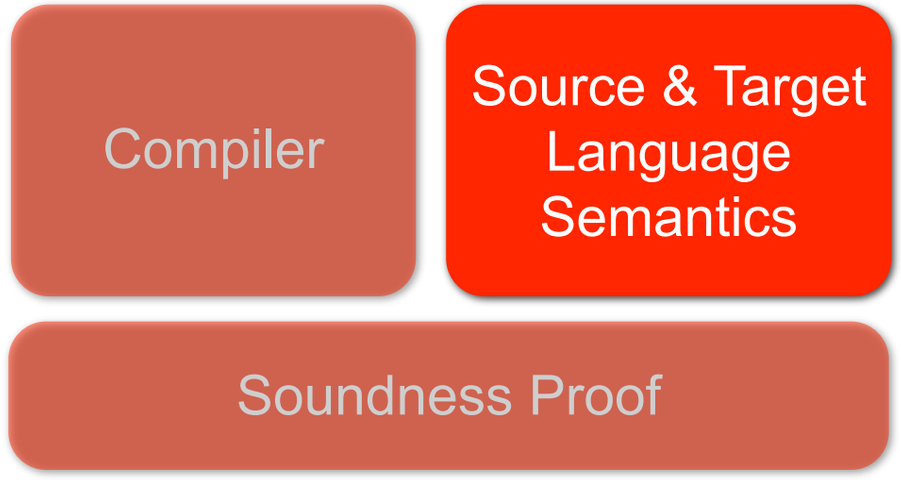

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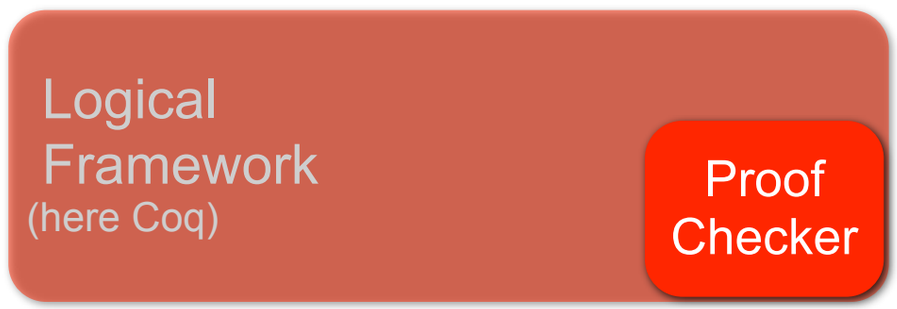

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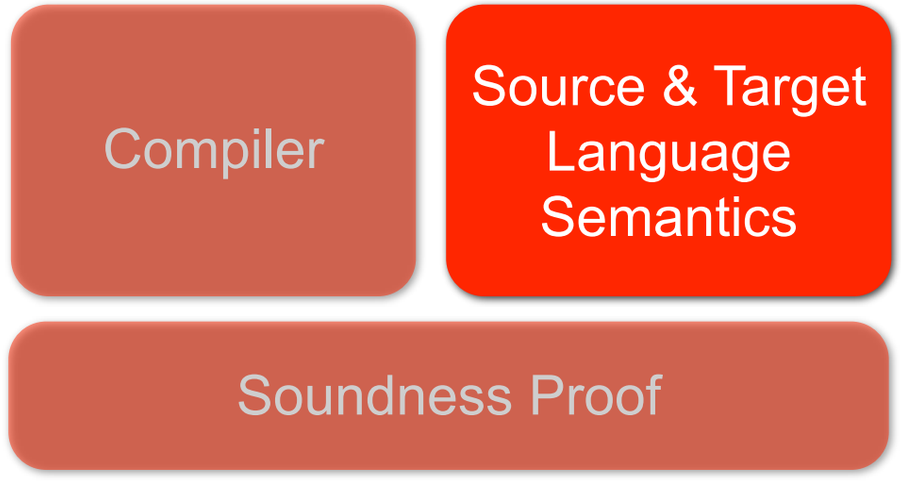

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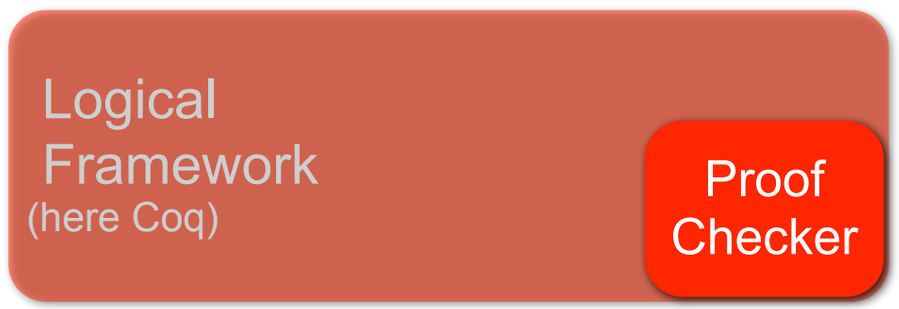


Still a large code base but at least a *foundational* code base: logic & semantics

The CompCert project

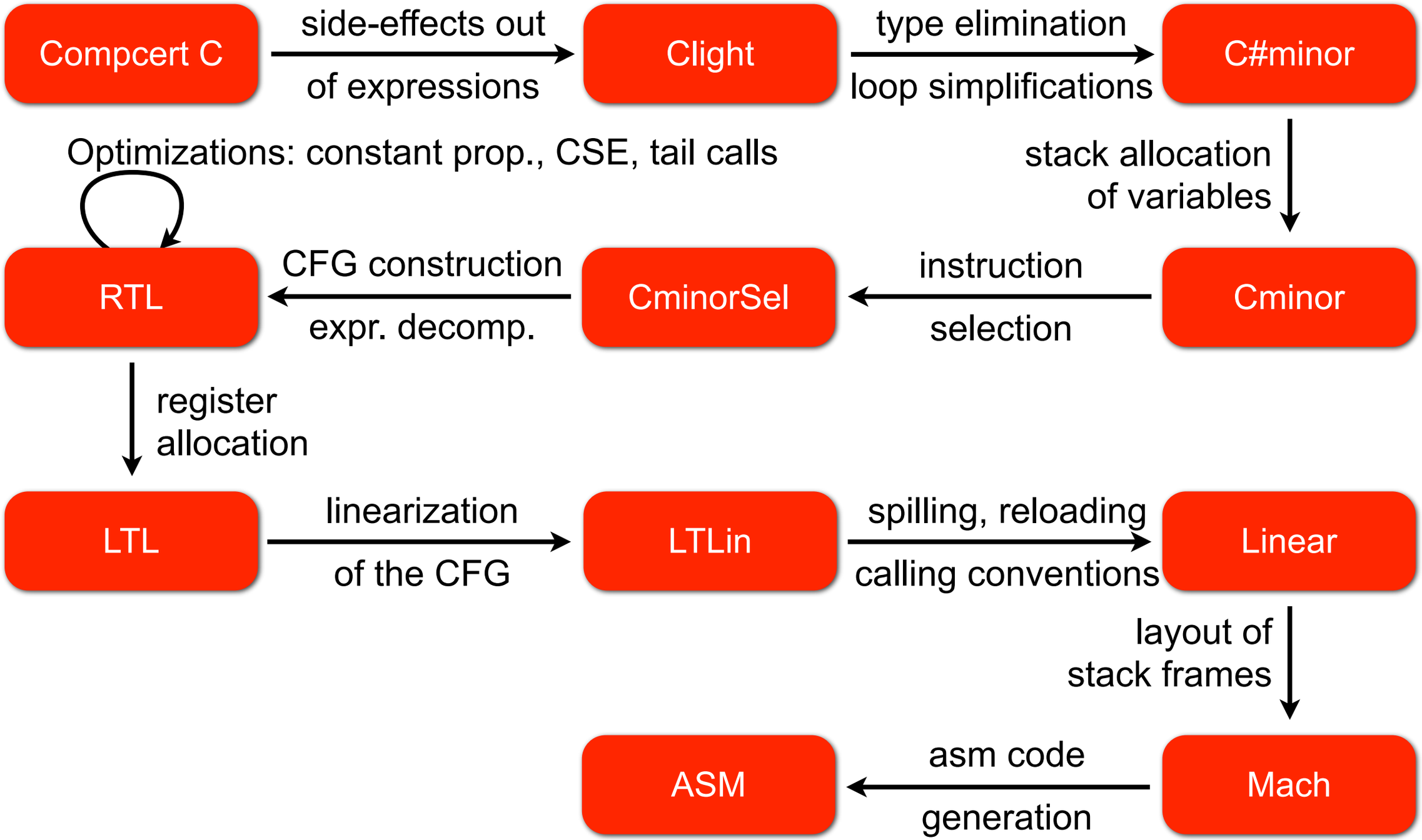
X. Leroy, S. Blazy et al.

Develop and prove correct a realistic compiler, usable for critical embedded software.

- Source language: a very large subset of C.
- Target language: PowerPC/ARM/x86 assembly.
- Generates reasonably compact and fast code
  ⇒ careful code generation; some optimizations.

Note: compiler written from scratch, along with its proof; not trying to prove an existing compiler
(otherwise see Zdancewic et al's Verified LLVM project).

The formally verified part of the compiler



Formally verified in Coq

After 50 000 lines of Coq and 4 person.years of effort

```
Theorem transf_c_program_is_refinement:
∀ p tp,
transf_c_program p = OK tp →
(∀ beh, exec_C_program p beh → not_wrong beh) →
(∀ beh, exec_asm_program tp beh → exec_C_program p beh).
```

Behaviors `beh` = termination / divergence / going wrong
+ trace of I/O operations (syscalls, volatile accesses).

Compiler verification patterns
(for each pass)

Compiler verification patterns

(for each pass)

Verified transformation

Compiler verification patterns

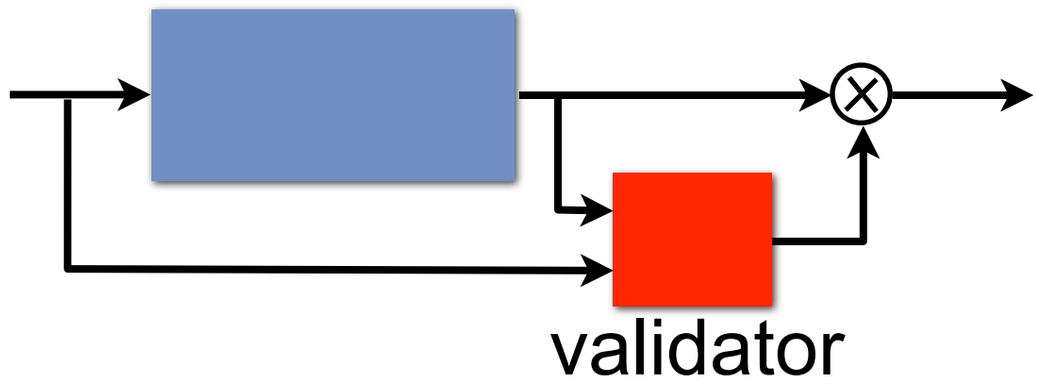
(for each pass)

Verified transformation

transformation

Verified translation validation

transformation



= formally verified

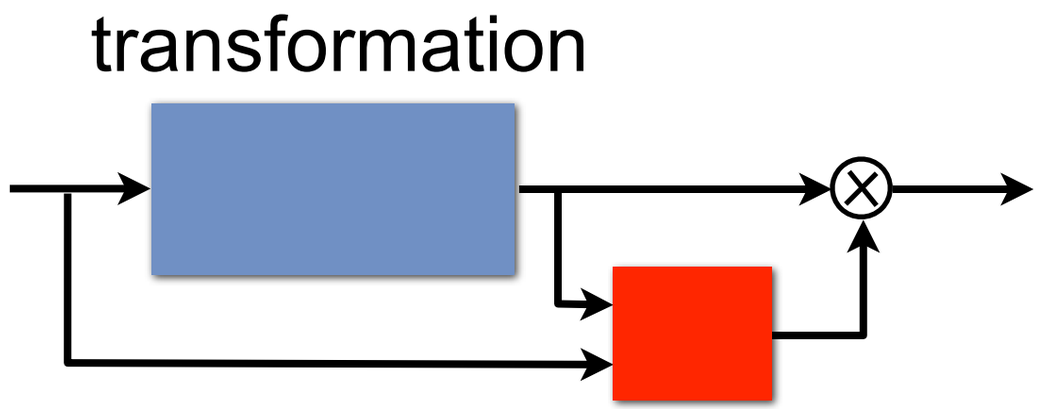
= not verified

Compiler verification patterns

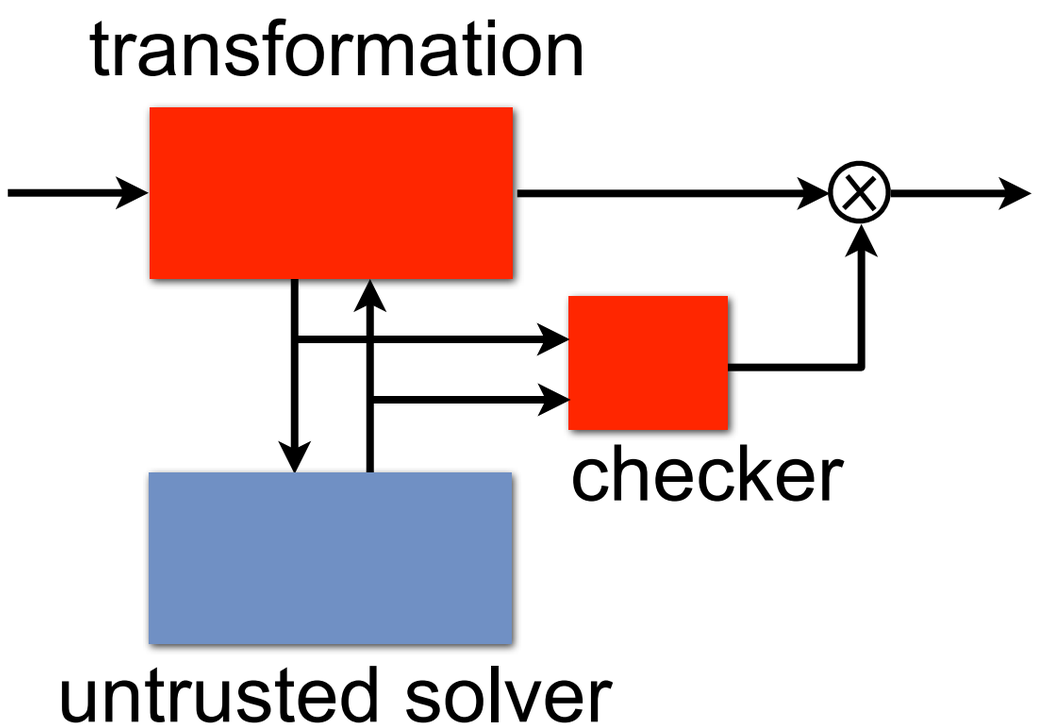
(for each pass)

Verified transformation

Verified translation validation



External solver with verified validation

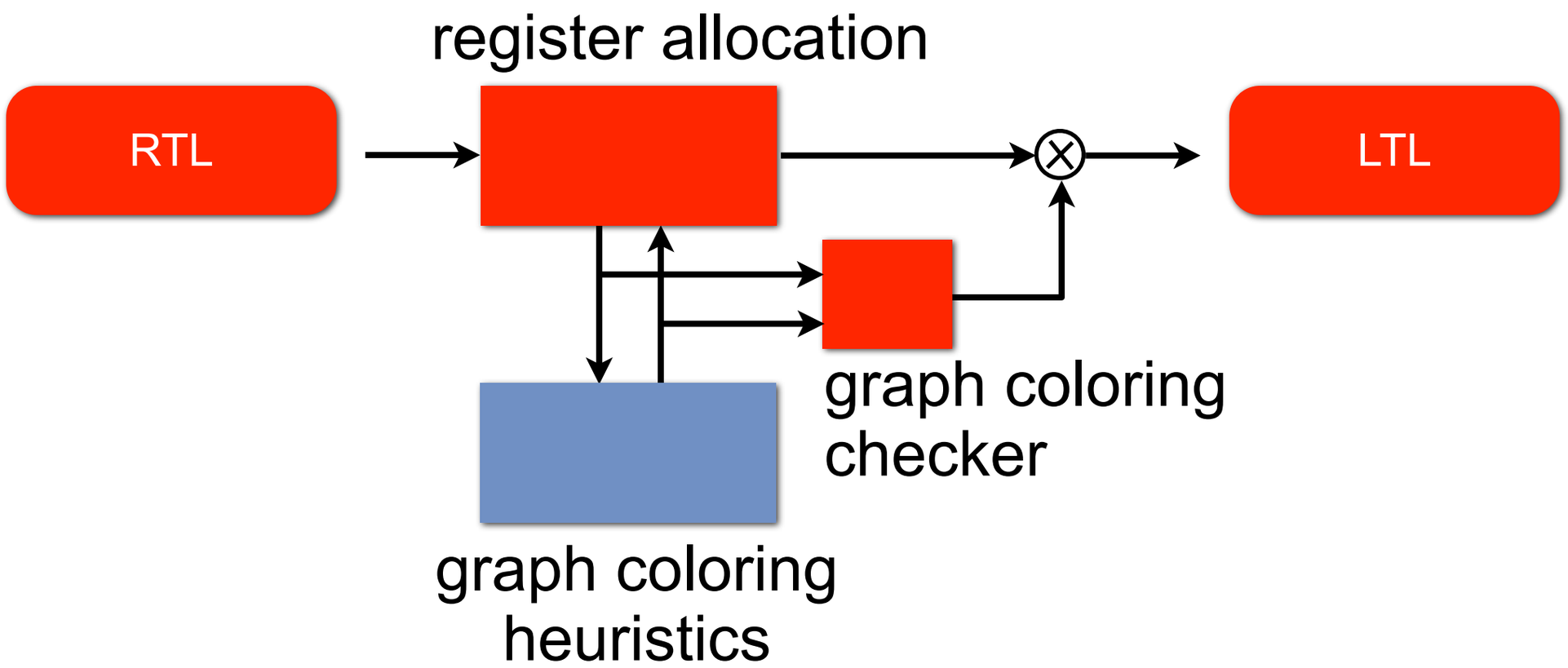


= formally verified

= not verified

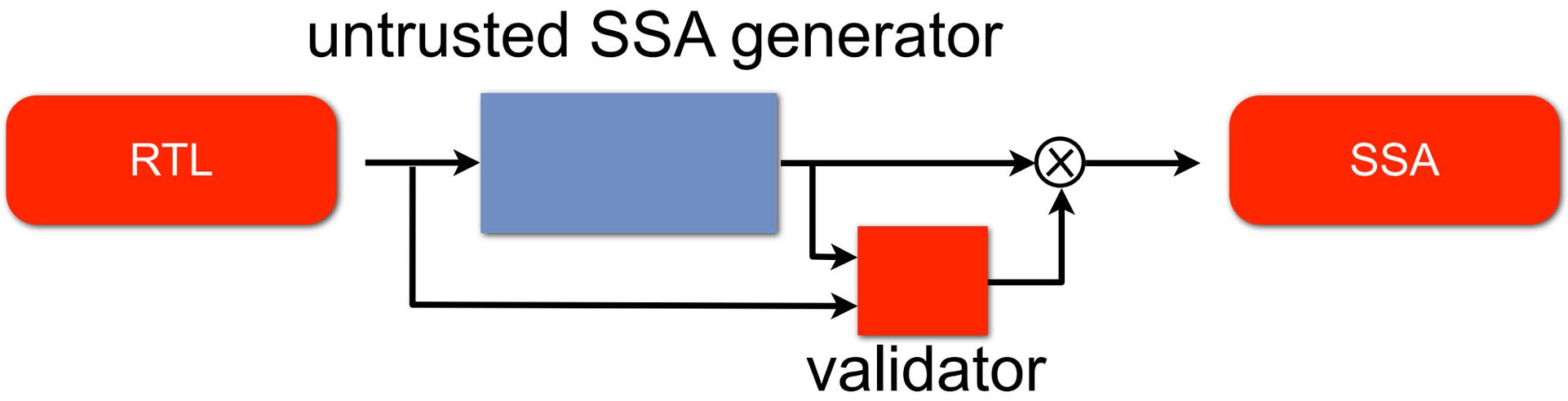
External solver with verified validation

Example: register allocation



Verified translation validation

Example: SSA generation (in CompCert SSA extension)



Verified translation validation

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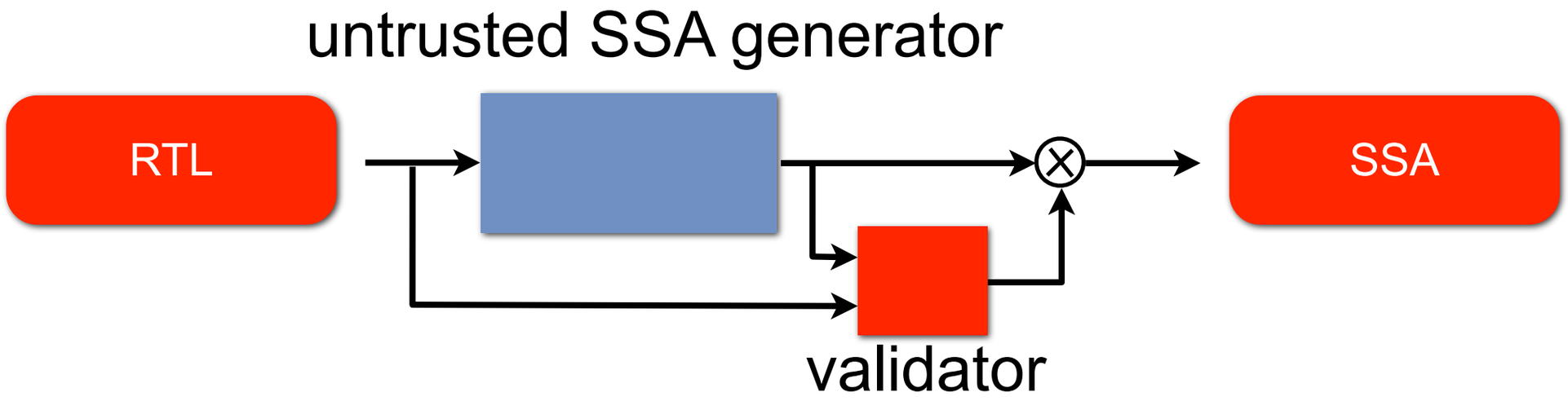

The untrusted generator can rely on advanced graph algorithms as Lengauer and Tarjan’s dominator tree construction and frontier dominance computation.

Verified translation validation

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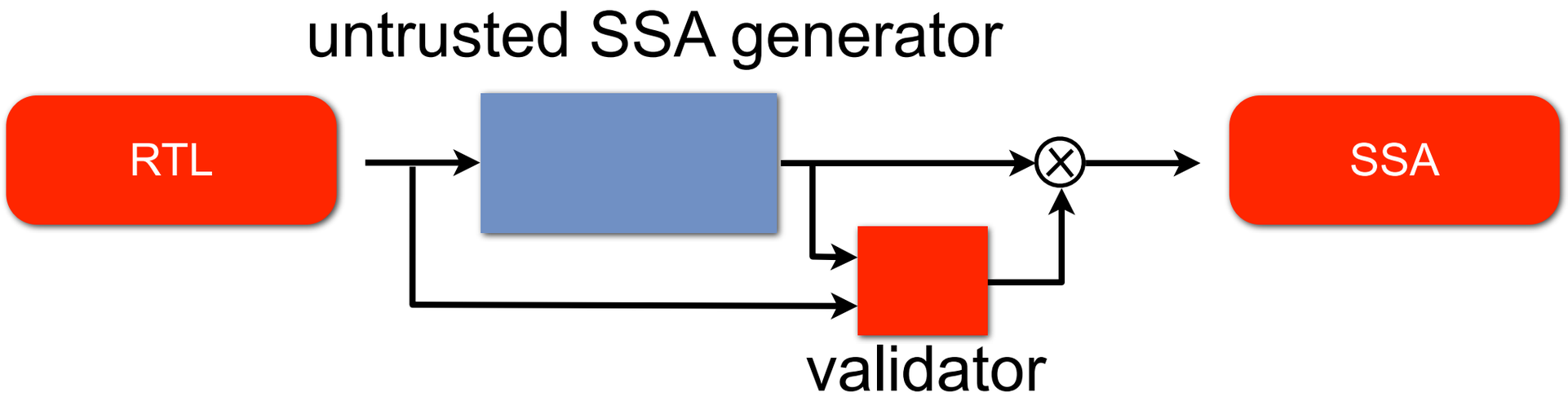

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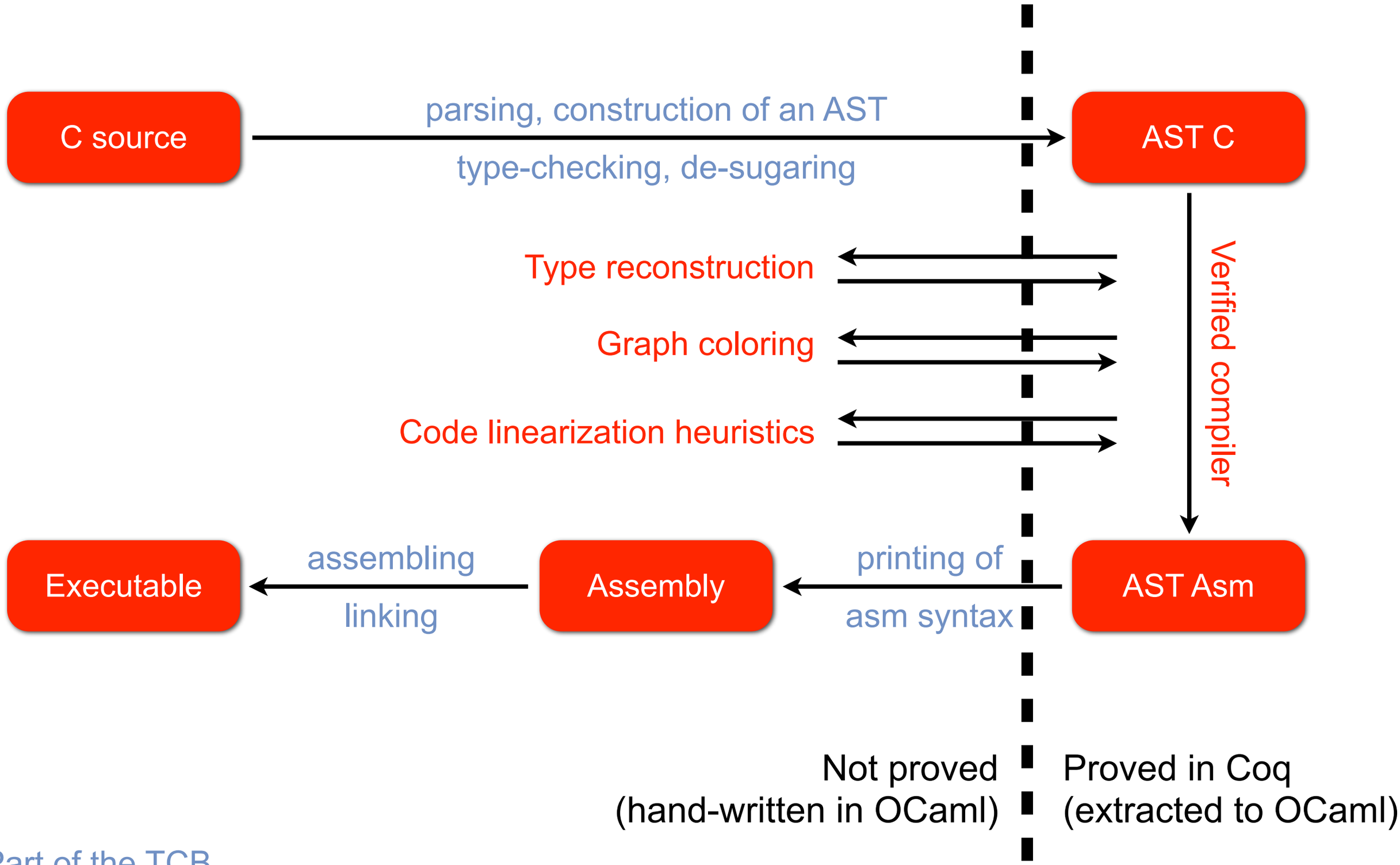
We prove the validator is *complete* with respect to this family of algorithms.

The whole CompCert compiler

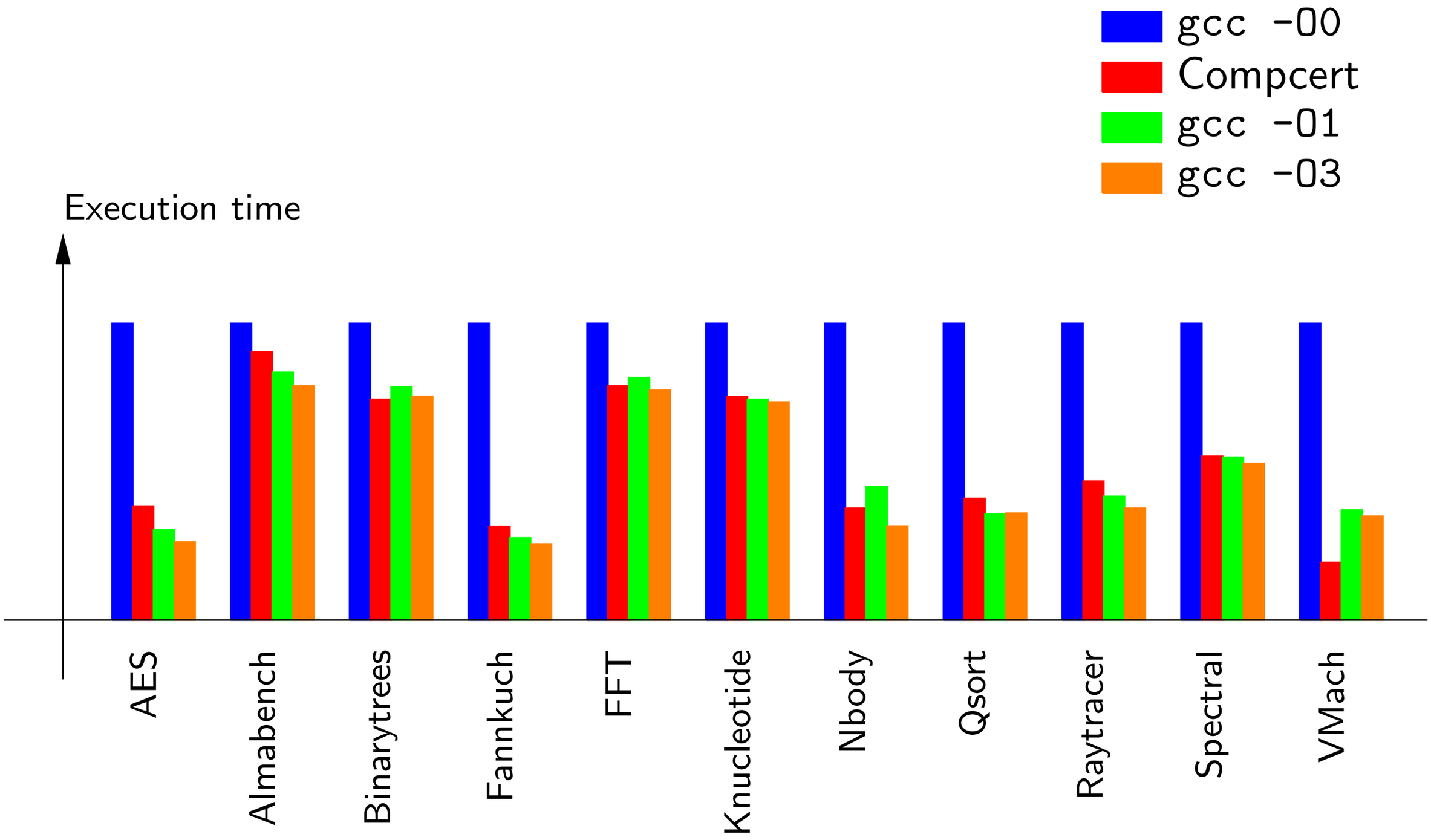


Part of the TCB

Not part of the TCB

Performance of generated code

(On a PowerPC G5 processor)



Conclusions

The formal verification of realistic compilers is feasible.

(Within the limitations of contemporary proof assistants)

Much work remains:

- Shrinking the TCB
  (e.g. verified parsing, validated assembling & linking).
- More optimizations
  (see CompCert SSA).
- Front-ends for other languages
- Concurrency
  (see Sevcik et al's CompCert TSO and Appel and al's Verified Software Toolchain).
- Connections with source-level verification
  (ongoing french project on a *verified* C static analyzer)