Formally Verifying Optimizations with Block Simulations

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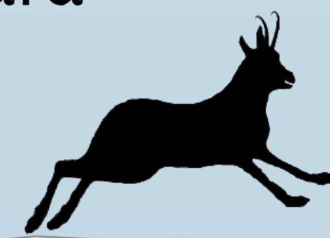
Formally Verifying Optimizations with Block Simulations

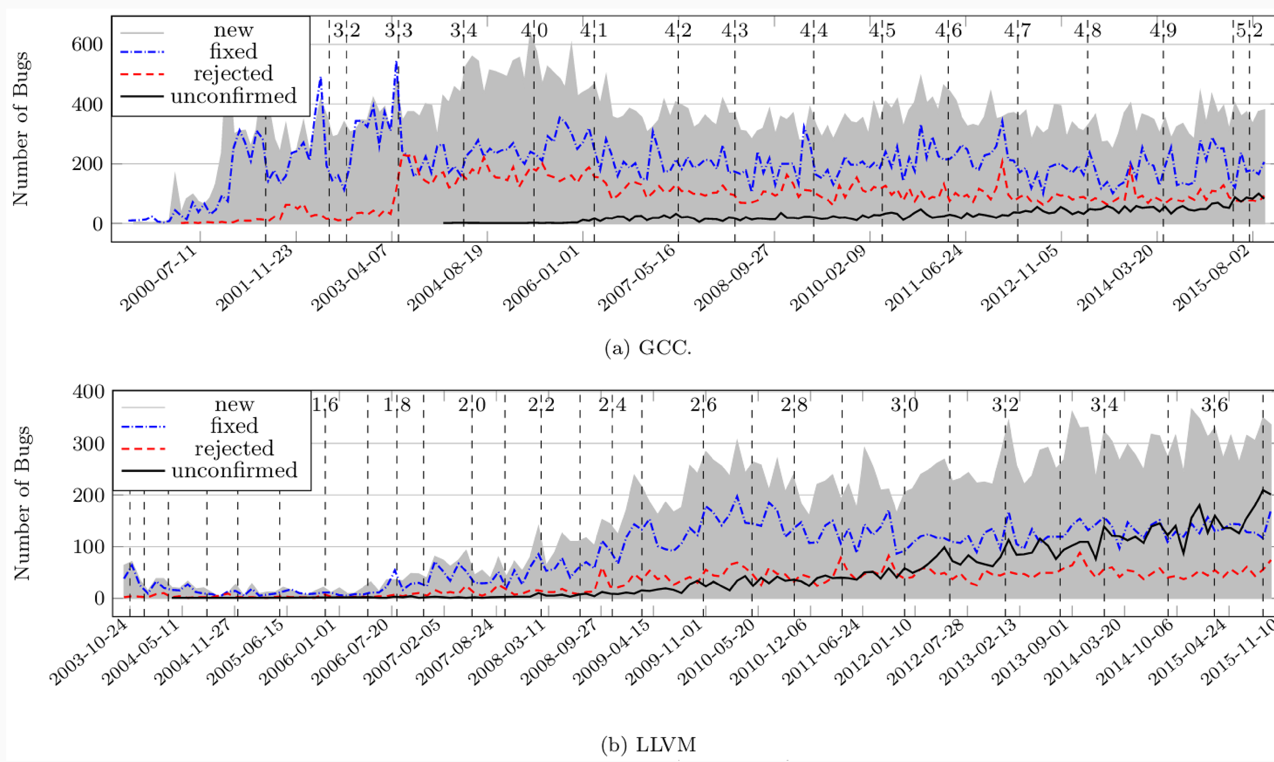
L. Gourdin, B. Bonneau, S. Boulmé, D. Monniaux & A. Bérard*

Université Grenoble Alpes, CNRS, Grenoble INP, Verimag

https://gricad-gitlab.univ-grenoble-alpes.fr/certicompil/Chamois-CompCert



Avoiding Bugs in GCC & LLVM (cf. [1])?



CompCert[1] **solution** (ACM Software System Award 2021): the 1st *formally verified* (= machine-checked mathematical proof of correctness) compiler optimizing **safety-critical** software [2, 3].

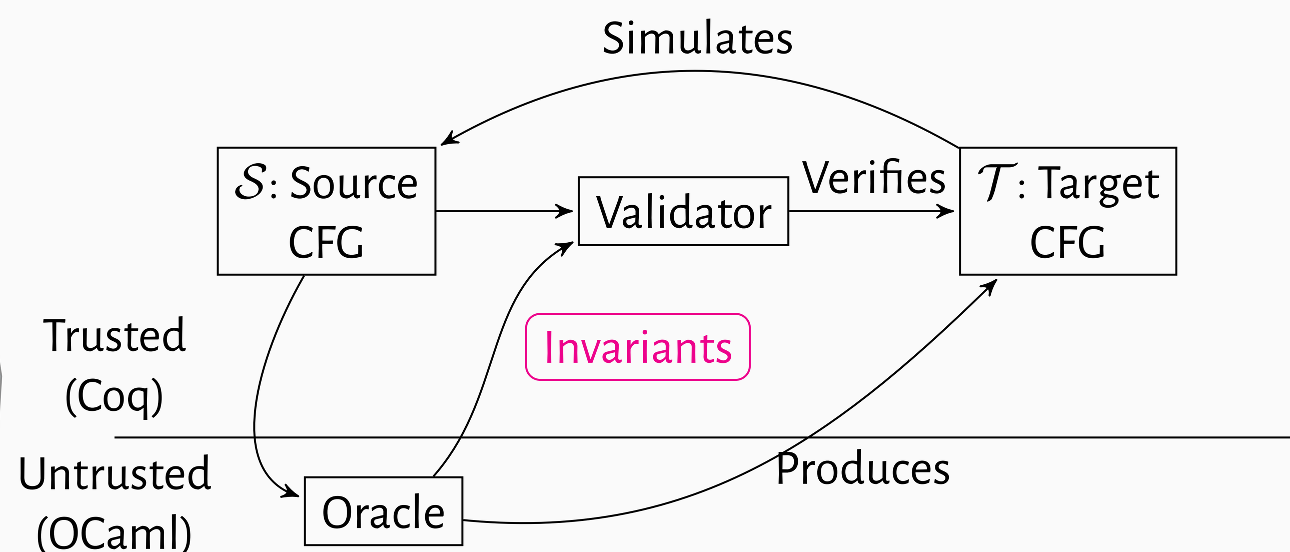
[1] https://www.absint.com/compcert/

Block Transfer Language

and its formally verified Translation Validator

The oracle takes source CFG $\mathcal{S}$ and yields its optimized version $\mathcal{T}$ along with an **invariant at the entry of each (loop-free) block**. Our verified symbolic simulation validator either ensures semantic preservation or aborts compilation.

Invariants express **relations between source and target states**.



Purposes of BTL TV

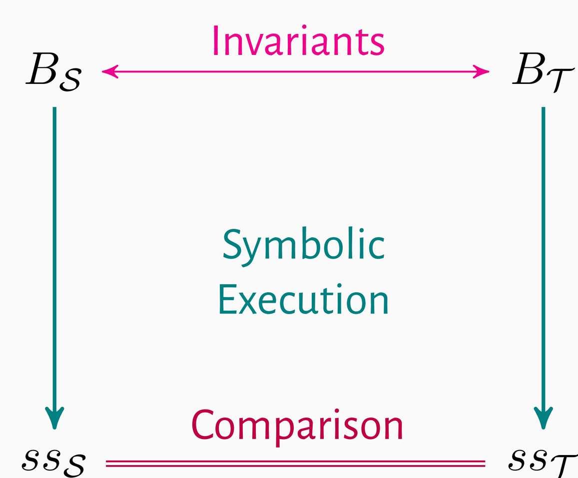
Block-by-block comparison of
a source CFG and
an oracle-provided target CFG
modulo oracle-provided invariants
and oracle-dependent rewriting rules

Features

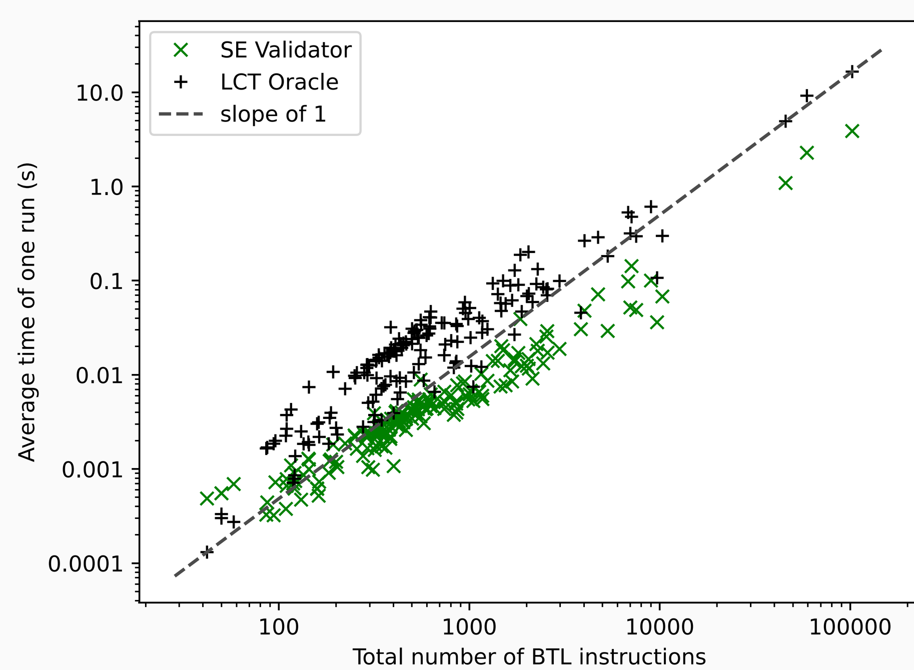
- Formally verified integration in Chamois-CompCert middle-end
- Parametrized by the architecture
- Predictible (against false alarms)
- Fast and Versatile
- **1st verified strength-reduction** of induction variables
- Validates various loop optimizations & *superblock scheduling* with code compensation and register renaming.

Block-by-block Symbolic Simulation

For each pair of blocks $(B_{\mathcal{S}}, B_{\mathcal{T}})$, it compares the symbolic *states* $(ss_{\mathcal{S}}, ss_{\mathcal{T}})$ resulting from their symbolic execution, themselves initialized from entry invariants: it tests equalities of exit invariants after normalized rewriting.



Compile Times That Scale (thanks to formally verified hash-consing)



Validating a Lazy Code Transformations Oracle

Combining and improving Lazy Code Motion [4] & Lazy Strength Reduction [5].

- Search for loop-invariant or "reducible" *candidates*;
- Supports decomposed patterns like a *left shift* + an *addition*;
- Based on data-flow analyses performed by an OCaml oracle;

```
void init7(long *t,
           unsigned long i,
           unsigned long l)
{ for (; i<l; i++) t[i]=7; }
```

C source code

Optimizing in two steps:

1. *Lifting* candidates out of the loop;
2. Inserting *compensation code* in the loop body if necessary.

Generating invariants from lifted computations and variables that remain live.

```
.L100: //NB: x0=0; x10=t; x11=i; x12=l
  bgeu x11,x12,.L101//exit if x11≥x12
  slli  x7,x11,3      // x7 = x11*2^3
  add   x13,x10,x7    // x13 = x10+x7
  addi  x5,x0,7       // x5 = 7
  sd    x5,0(x13)     // *x13 = x5
  addi  x11,x11,1     // x11 += 1
  j     .L100
```

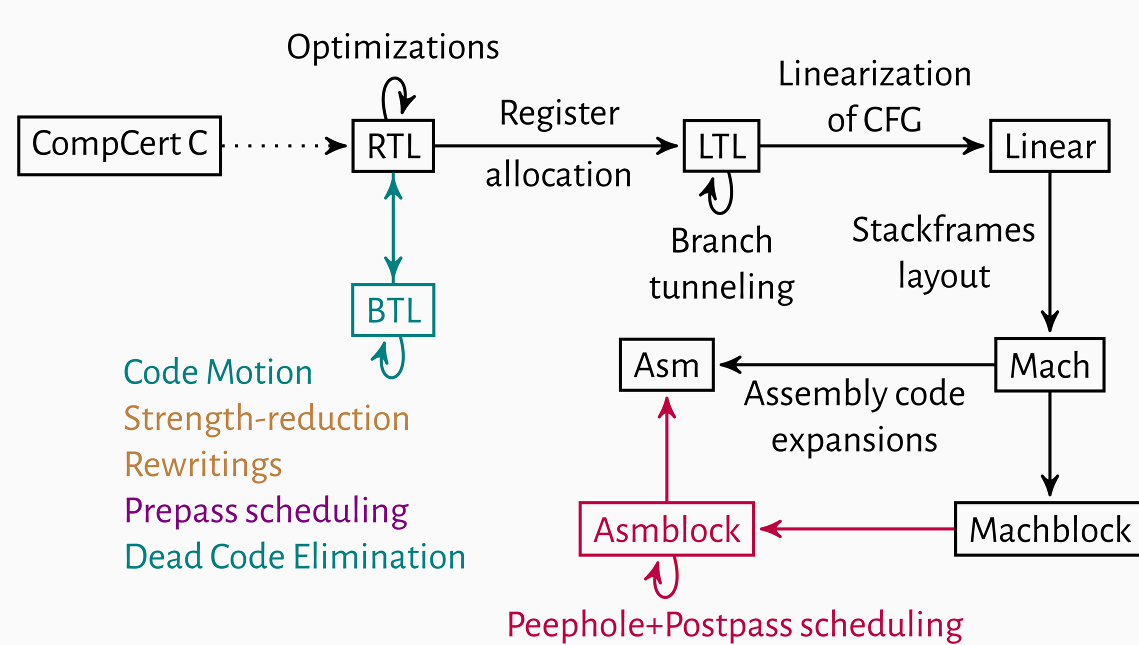
RISC-V ASM Before

→

```
  slli  x7,x11,3      // x7 = x11*2^3
  add   x13,x10,x7    // x13 = x10+x7
  addi  x5,x0,7       // x5 = 7
.L100:
  //invariant x5_T = 7 ∧ x13_T = x10_S+x11_S×8
  //           ∧ x11_T = x11_S ∧ x12_T = x12_S
  bgeu  x11,x12,.L101//exit if ...
  sd    x5,0(x13)     // *x13 = x5
  addi  x13,x13,8     // x13 += 8
  addi  x11,x11,1     // x11 += 1
  j     .L100
```

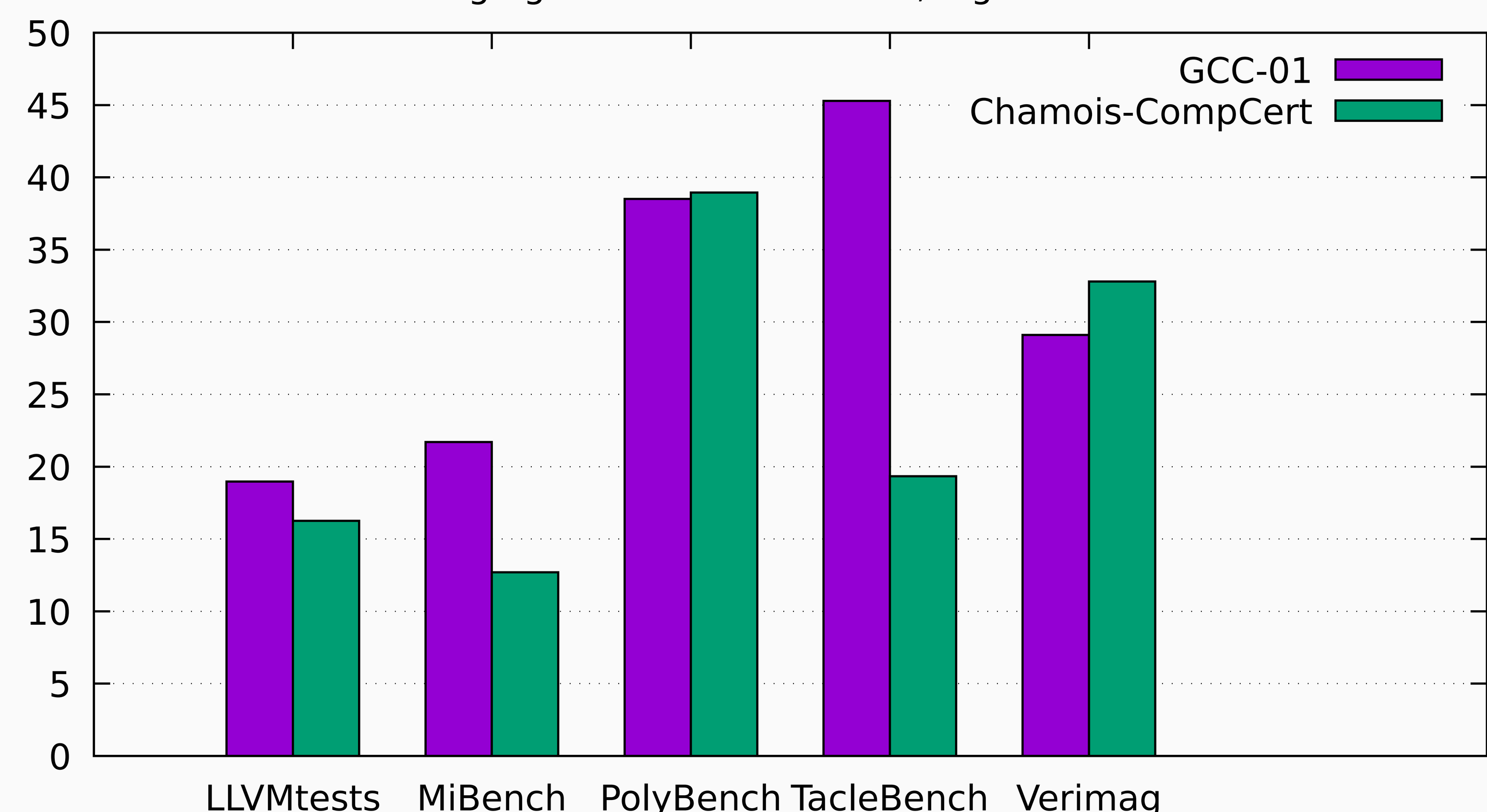
RISC-V ASM After

Chamois-CompCert Optimizations



Legend:
Brown: **RISC-V** only
Violet: AArch64 +ARMv7+**RISC-V**+KVX
Red: AArch64 +KVX
Teal: All (AArch64 +ARMv7+**RISC-V**+KVX +PPC+x86)

Optimized Generated Code That You Can Trust



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[1] Chengnian Sun et al. "Toward understanding compiler bugs in GCC and LLVM". en. In: *Proceedings of the 25th International Symposium on Software Testing and Analysis*. Saarbrücken Germany: ACM, 2016, pp. 294–305. ISBN: 978-1-4503-4390-9. DOI: 10.1145/2931037.2931074. URL: https://dl.acm.org/doi/10.1145/2931037.2931074 (visited on 06/17/2022).

[2] Xavier Leroy. "Formal verification of a realistic compiler". In: *Communications of the ACM* 52.7 (2009). DOI: 10.1145/1538788.1538814.

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[4] Jens Knoop, Oliver Ruthing, and Bernhard Steffen. "Optimal Code Motion: Theory and Practice". In: *ACM Transactions on Programming Languages and Systems* 16 (1995). DOI: 10.1145/183432.183443.

[5] Jens Knoop, Oliver Rüthing, and Bernhard Steffen. "Lazy Strength Reduction". In: *Journal of Programming Languages* 1 (1993), pp. 71–91.

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