Formally Verified Advanced Optimizations for RISC-V

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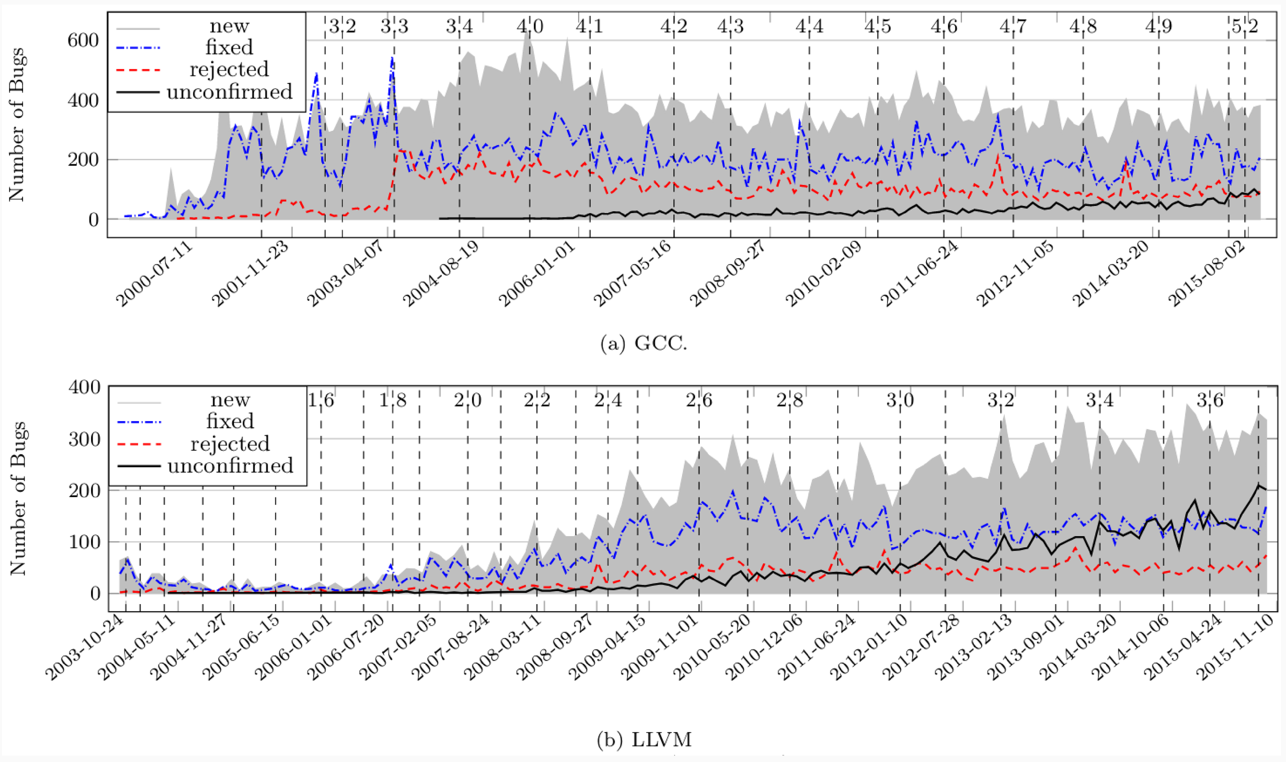
https://gricad-gitlab.univ-grenoble-alpes.fr/certicompil/Chamois-CompCert

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/

Our goal:

verified RISC-V optimizations

Reduced ISA & In-order cores

⇒ clever optimizations needed!

E.g. way simpler addressing modes:

```
ldr  x0,[x0,w1,sxtw#3]
```

Aarch64 (ARMv8-A)

```
slli  x6,x11,3
add   x6,x10,x6
ld    x6,0(x6)
```

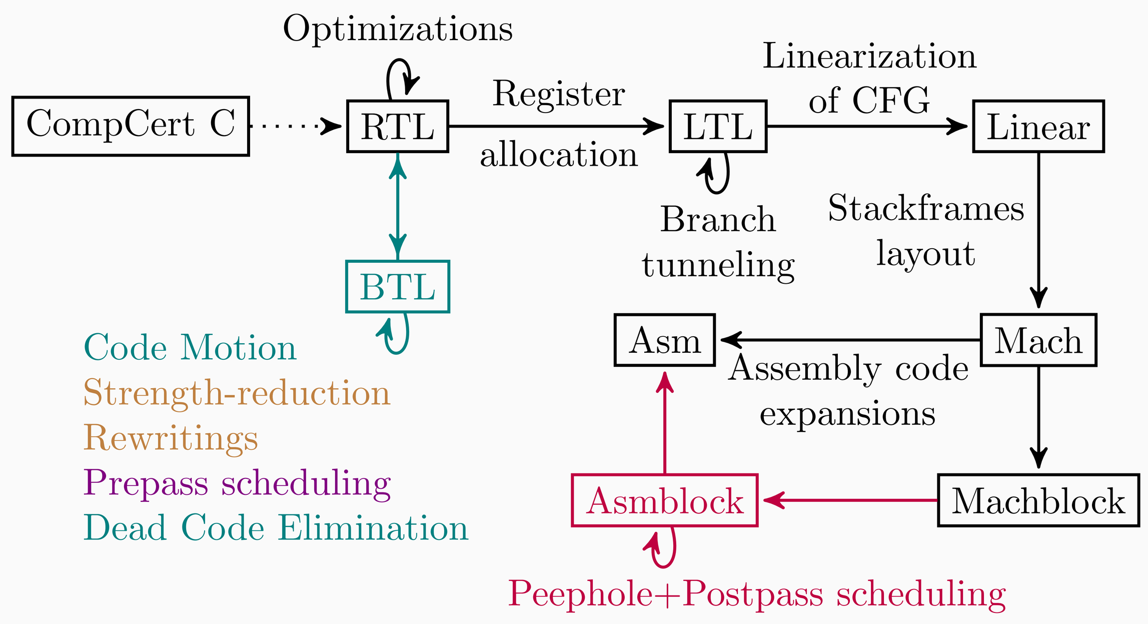
RISC-V

Our solution:

a versatile validation framework

- Supports many optimizations;
- Independent of the architecture;
- **1st verified strength-reduction** of induction variables.

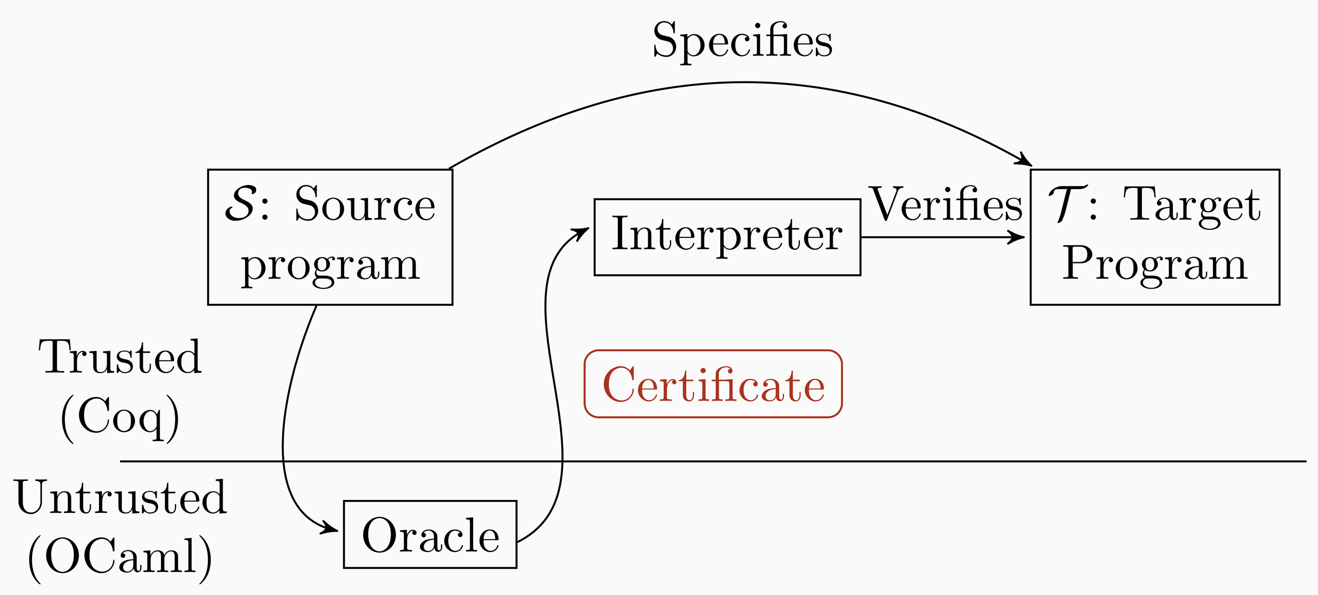
Chamois-CompCert Extensions



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

Our General Purpose Translation Validator

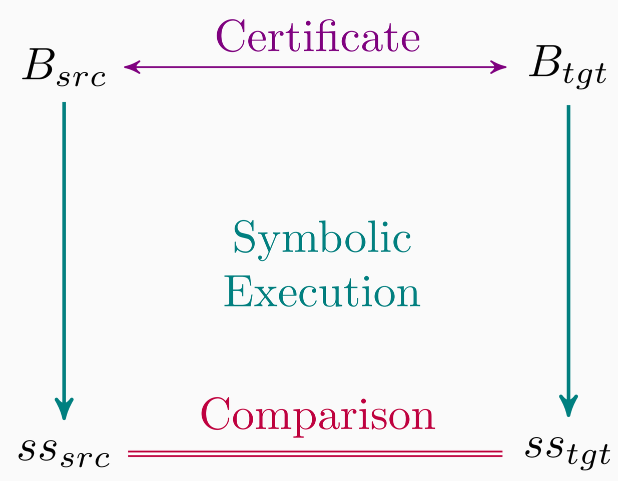
The oracle takes source program $\mathcal{S}$ and yields its optimized version $\mathcal{T}$ along with a certificate. A verified symbolic execution interpreter then ensures semantic preservation, and aborts compilation in case of failure.



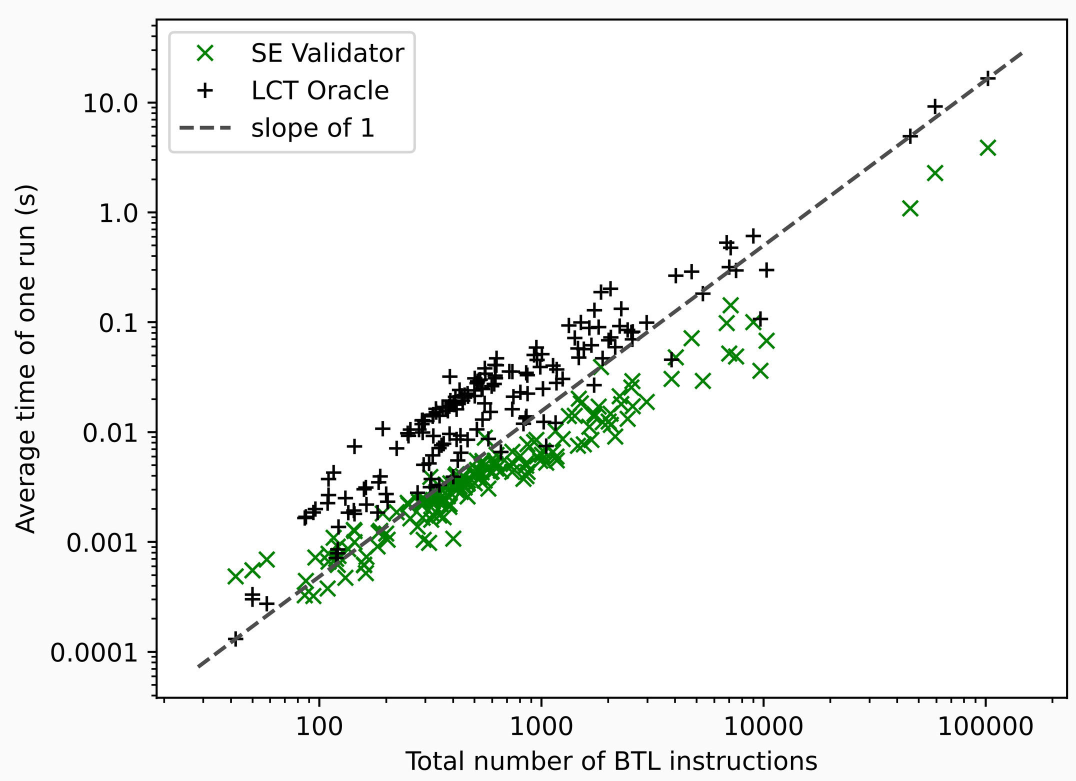
Defensive Symbolic Simulation

For each pair of loop-free blocks ($B_{src} \in \mathcal{S}, B_{tgt} \in \mathcal{T}$); we compare the symbolic *states* (ss_{src}, ss_{tgt}) resulting from their symbolic execution.

The certificate contains *invariants* propagating information between blocks.



Compile Times That Scale



Validating the Lazy Code Transformations Oracle

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

- Search for *reducible* multiplicative operators;
- Based on data-flow analyses performed by an OCaml oracle;
- Supports decomposed patterns like a *left shift* + an *addition*;

Optimizing in two steps:

1. *Lifting* the multiplication out of the loop;
2. Inserting *compensation code* in the loop body.

```
long main(long x, long n) {
  long i = 0;
  while (i < n) {
    x += i * 5;
    i += 3;
  }
  return x;
}
```

C source code

```
main:
  [...]   //prelude
  addi  x12, x0, 0   //i=0
.L100:
  slli  x7, x12, 2  //t=i*4
  add   x6, x12, x7 //t=i*4+i=i*5
  bge   x12, x11, .L101 //i>=n?
  add   x10, x10, x6 //x+=t
  addi  x12, x12, 3 //i+=3
  j     .L100
```

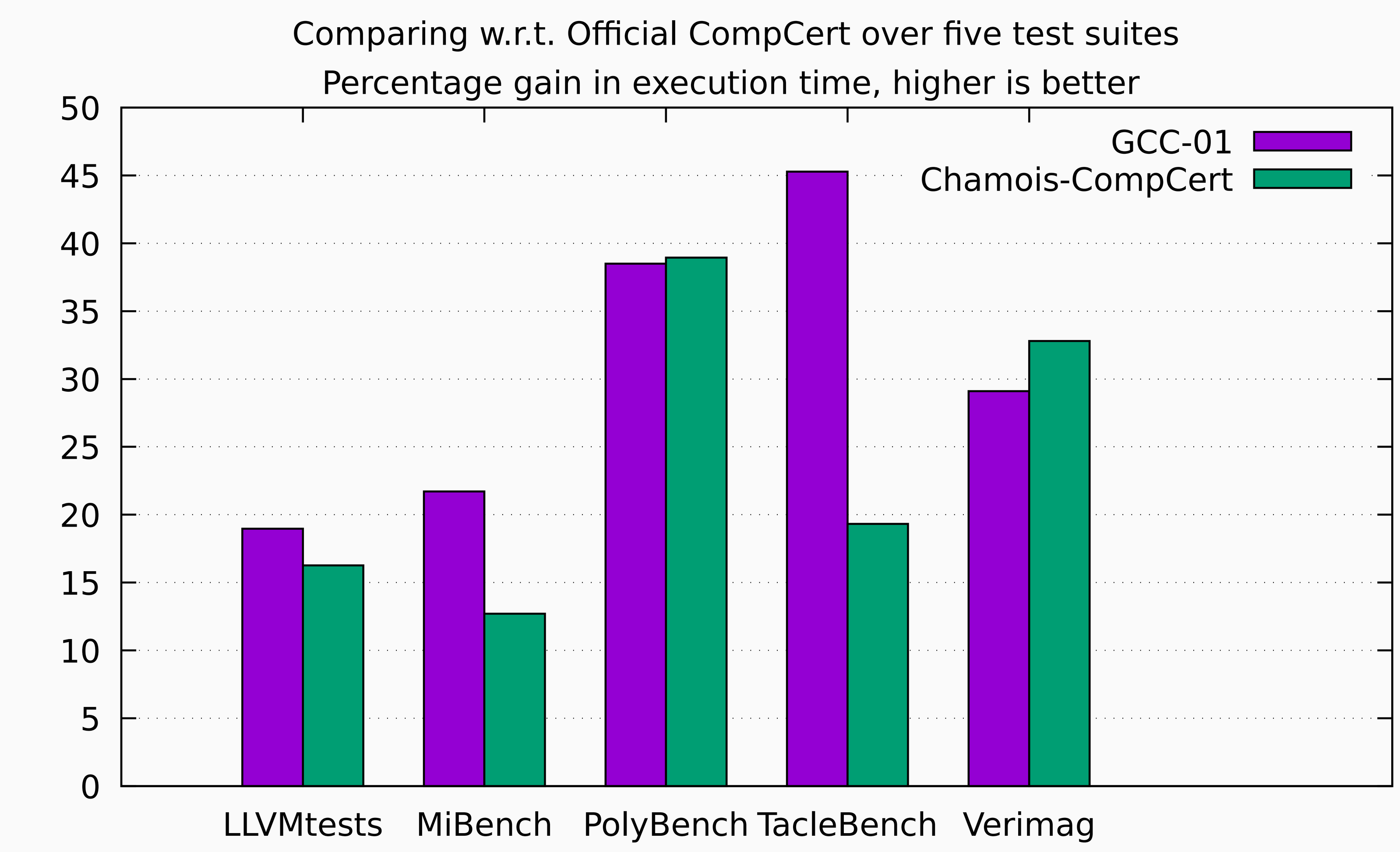
RISC-V ASM Before

→

```
main:
  [...]   //prelude
  addi  x12, x0, 0
  slli  x7, x12, 2
  add   x6, x12, x7
.L100:
  bge   x12, x11, .L101
  add   x10, x10, x6
  addi  x6, x6, 15 //t+=15
  addi  x12, x12, 3
  j     .L100
```

RISC-V ASM After

Optimized Generated Code That You Can Trust



References

[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.

[3] Daniel Kästner et al. "CompCert: Practical experience on integrating and qualifying a formally verified optimizing compiler". In: *ERTS 2018: Embedded Real Time Software and Systems*. SEE, 2018.

[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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