Progress in Formal Verification of Compilers: A Survey

CS410P/510 Programming Language Compilation
Winter 2024

What?

- **Compiler**:

  Source Language → Compiler → Target Language

- **Correctness**:

  if t = compile(s)

  then behavior(t) matches behavior(s)

  - for suitable definition of behavior and matching

- (Mechanized) **Verification**:

  give a mechanically checked proof of correctness on all programs

Why?

- Real compilers have **bugs**, but verified ones have fewer:

The striking thing about our CompCert results is that the middle-end bugs we found in all other compilers are absent. As of early 2011, the under-development version of CompCert is the only compiler we have tested for which Csmith cannot find wrong-code errors. This is not for lack of trying: we have devoted about six CPU-years to the task. The apparent unbreakability of CompCert supports a strong argument that developing compiler optimizations within a proof framework, where safety checks are explicit and machine-checked, has tangible benefits for compiler users

- [Yang+11]

Why? (2)

- Verifying algorithms helps us **understand** them much better
  - Especially useful to tame the “optimization zoo”
- Formal verification requires formal **specification** of language semantics (behavior) and semantic preservation (matching)
  - Not easy to get right!
  - Useful for many other tasks…

Compiler Verification in Context

Possible goals involving formal semantics of L:

- Verifying "**meta-properties**" of language L
  - e.g. well-typed L programs don't crash at runtime
- Verifying properties of **particular** L programs
  - e.g. this L function computes square roots correctly
- Verifying properties of **transformations** on L
  - e.g. this compiler from L to assembly code is correct
- In practice, there is overlap, e.g. language RTS.

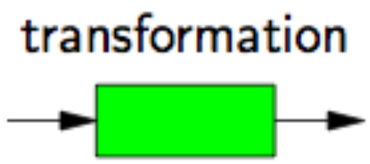
Two Schools of Mechanized Proof

- Interactive Provers ("proof assistants")
  - Finding proof is not fully automated
  - Checking is fully automated (and trustworthy)
  - Logics can be very expressive
  - Examples: Coq Isabelle ACL2 PVS HOL etc.
- Automatic Provers
  - Finding proof (or refutation) is fully automated
  - Logics strictly limited in power (e.g. no quantifiers)
  - Can handle very large problems
  - Examples: Z3 CVC Simplify etc.

Defining Compiler Correctness

- Key idea: **observable** properties of source behavior should also be properties of target
  - e.g. trace of IO system calls
  - note: internal behavior is generally **not** preserved!
- Hence, target code should only do things source code might do (**simulation/refinement**)
- In practice, many tricky technical issues:
  - non-termination, error behaviors, granularity of comparison, etc.

Verify or Check?



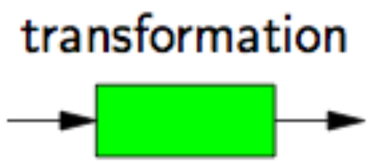
Two approaches to verification:

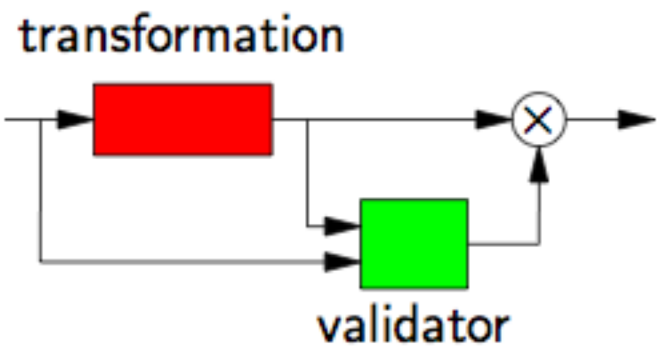
- **verified transformations**
  - are directly proven to preserve observable behavior
  - typically by showing they preserve (internal) invariants
  - compiler must be a “white box” (probably one we wrote)

Verify or **Check?**

Two approaches to verification:

- (verified) **translation validation**
  - on each run, check that compiler output is correct; otherwise fail-stop
  - we must hope it seldom fail-stops!
  - compiler can be a “black box” (maybe) or a “gray box”
  - (must prove checker is correct)





- most clearly a win if checking output is easier than generating it

Toy Example in Coq

- To make these ideas concrete, consider an extremely simple "compiler" from arithmetic expressions

  e := x | n | e + e | e – e |e *e

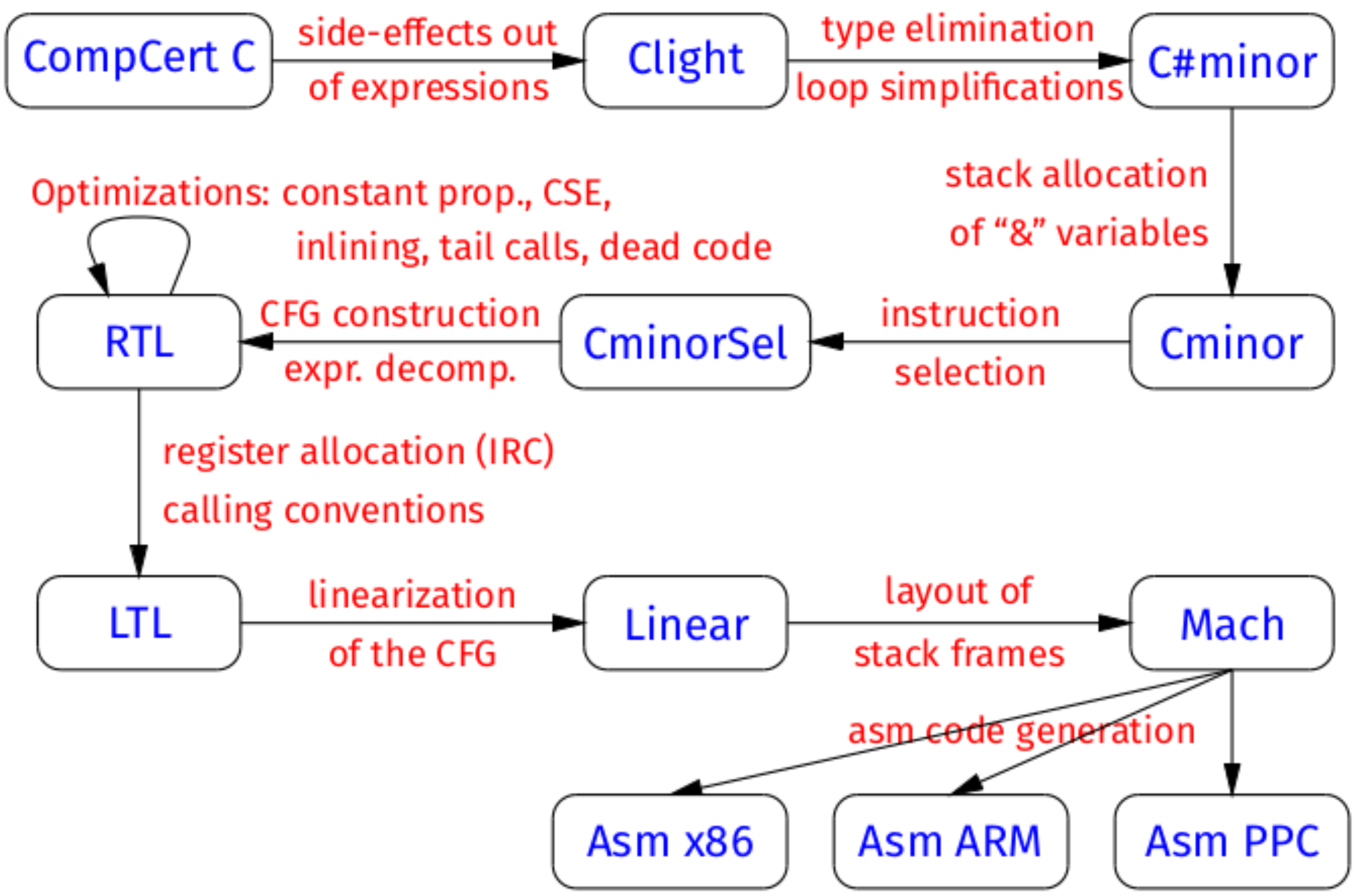
  to stack-machine code

  i := Push n | Load x | Plus | Minus | Mult
- See compver.v

The CompCert C Compiler

- [Leroy+06] See http://compcert.inria.fr
- Goal: A verified production-quality C compiler usable for critical embedded software
- Source language: (most of) C
- Target language: PPC, ARM, or X86 assembler
- Coq is used for proof and to implement (most of) the compiler itself (using extraction)
- Generates respectable target code, but does little optimization

Compiler Pass Structure



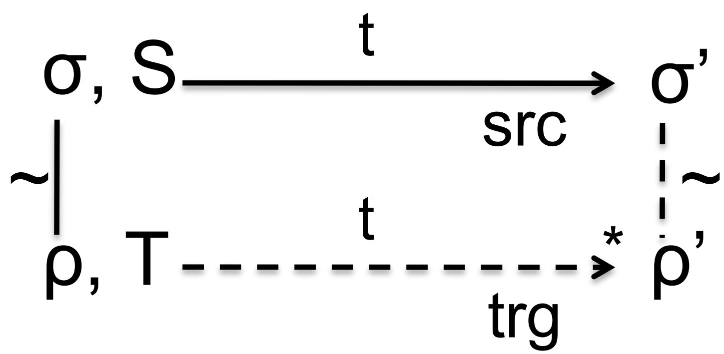
(from CompCert web site)

CompCert Proof Structure

- Formal semantics for each IR
  - "adequacy" is a concern at endpoints
- Composition of preservation proofs for individual pipeline stages
- Mostly directly verified transformations, but some phases use translation validation
  - e.g. register allocation: much easier to validate an allocation solution (and prove the validator correct) than to prove precise spec for allocator

Forward Simulation Proofs

- Correctness of most phases is proven by establishing a simulation relation like this:



S = src prog
T = target prog
σ = src state
ρ = target state

- Core of proof is defining state relation ~
- Each phase preserves the trace t of observable events (e.g. system calls)
- This strategy relies on languages being deterministic

CompCert Memory Model

- An important simplifying idea is to use the same memory model for all phases
- Memory is unbounded set of distinct blocks, each with individual bounds
  - each global, stack frame, and alloc gets own block
  - pointer arithmetic allowed only within blocks
- Although this simplification is a strength, it means that assembler semantics are less concrete than we might like…

CompCert status

- ca. 100K lines of Coq program and proof, 6 person years [as of 2018; somewhat more now]
- Some industrial users (e.g. Airbus)
- Many research groups have built on CompCert framework
  - optimizations
  - weak memory models
  - verified program analysis tools

Decompilation (1)

- Decompiling machine code[Myreen09,etc]
  - Build (certifiably) equivalent functional program
    - Each instruction becomes a sequence of updates and a collection of side conditions
    - Control flow is analyzed to discover loops
  - Can use to build a translation validator
    - Assuming we have effective automated equivalence checking between source & decompiled programs
    - Favors gray box approach
    - Limited support for optimization

Decompilation (2)

- Translation validation of seL4 [Sewell+13]
  - Used to transfer functional correctness proof from C to ARM machine code
  - Validated gcc compilation of 9500 C line kernel
    - almost 100% at –O1 (1 hour); about 55% at –O2 (4.5 hours)
  - C code and decompiled machine code both converted to a graph IR (unverified)
  - Equivalence of graph IRs checked by external SMT solvers (Z3 and SONOLAR).

Summary

- Verification of (new) production-quality compilers is well within reach today
- Verified translation validation is a promising technique for use with existing compilers
- Many foundational and engineering research challenges remain
- Why verify? To understand what you're doing!

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