Designing Self-Certifying Compilers

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Compilers are Everywhere!

- **Language Implementation**
  - C/C++ to a.out
  - Java/Python to bytecode
  - VHDL/Verilog to netlist
  - Statecharts to C++

  Target behavior should be a subset of source behavior.

- **Refactoring Programs**
  Source and target behavior should be identical.

- **Layering Program Aspects**
  Target should match source behavior on all but the new aspect.
What is the Problem?

Compilers are too large and far too complex for *ex post facto* verification.
This is not a new problem!

But I called this a minor cause; the major cause is ... that the machines have become several orders of magnitude more powerful! To put it quite bluntly: as long as there were no machines, programming was no problem at all; when we had a few weak computers, programming became a mild problem, and now we have gigantic computers, programming has become an equally gigantic problem.

(The Humble Programmer, Edsger W. Dijkstra, 1972)
This talk: A Less-Than-Ideal Solution

Design software to be self-certifying.

With the property: If $\text{valid}(\text{In}, W, \text{Out})$ then Box is operating correctly.

Proof/Witness/Certificate
Does self-certification work for compiling?

Common optimizations have simple certificates

- Dead Store Elimination
- Constant Propagation and Folding
- Loop Unrolling (replicate loop body)
- Loop Peeling (expand first K iterations)
- Loop Invariant Code Motion
- Static Single Assignment (SSA) conversion
- CFG simplification
- Instruction Combination

The trusted code base shrinks from a few million to a few thousand lines of code.

Credible Compilation [Rinard-Marinov, 1999]
Witnessing [Namjoshi-Zuck, 2013]
What is a Certificate?

There is a simple pattern to the certificate:
-- relate states with the same program location, and
-- include term $v = v'$ if and only if variable $v$ is \textbf{live} at that location in the source program.
What is a Certificate?

This certificate also follows a simple pattern:
-- relate states that have the same location, and
-- include term $v = v'$ for all variables $v$, and term $v = c$ if $v$ has a known constant value $c$ at that location in the source.
Validating Certificates

**Soundness:** Every computation of T has a W-related computation in S with identical i/o behavior.

**Completeness:** Every correct transformation has a valid certificate.

The certificate may include **history** (summarize past actions), allow **stuttering** (ignore inessential actions), and provide **prophecy** (guess future nondeterminism).
Generating Certificates

There is a simple pattern to the certificate:
-- link states with the same program location, and
-- include term \( v = v' \) if and only if variable \( v \) is live at that location in the source program.
... And Checking Them

The checker turns the validity constraints into SMT queries.

\[
\begin{align*}
x & = x' \quad \text{and} \quad y = y' \\
\text{x := } x+y & \quad \text{skip} \\
y & = y' 
\end{align*}
\]

The induced SMT query is

\[
\begin{align*}
x & = x' \quad \text{and} \quad y = y' & \quad \text{// top W} \\
\text{and} \quad \text{next}(x') & = x' \quad \text{and} \quad \text{next}(y') = y' & \quad \text{// skip} \\
\text{and} \quad \text{next}(x) & = x + y \quad \text{and} \quad \text{next}(y) = y & \quad \text{// x := x+y} \\
\Rightarrow \quad \text{next}(y) & = \text{next}(y') & \quad \text{// bottom W}
\end{align*}
\]
Certificate Generation for LLVM

![Graph showing Comment-Free Lines of Code for different optimizations: loopunroll, dce, mem2reg. The x-axis represents the number of comment-free lines of code from 0 to 700. The graph includes bars for Original LLVM Opt., C++/LLVM Gen., and OCaml Gen.](image-url)
Open: Concurrency-aware Optimization

Standard optimizations may be incorrect for concurrent execution.

```plaintext
x := 1; y := 1;
signal A; await A;
await B; print x;
print y; signal B;
```

```
skip; skip;
signal A; await A;
await B; print x;
print y; signal B;
```

Prints x=1, y=1

Prints x=0, y=0

How to certify concurrency-aware transformations?
Correct optimizations can introduce security holes.

```plaintext
x := read_password();
use(x);
x := 0; // clear memory
// password is secure
```

```plaintext
x := read_password();
use(x);
x := 0; // dead store
// password leaks via x
```

How to certify secure compilation?
To Sum Up

• Much software is too large and far too complex to be verified *ex post facto*. It is necessary to **build verifiability into software**.

• The design of self-certifying software is an art .... but one that is informed by deductive proof principles.

**Design your software to be self-certifying!**
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Spinoff: Defensive Optimizing Compilation

Can an optimizing compiler make good use of externally generated invariants?

**Theorem:** If $R$ is a refinement from $T$ to $S$ and $\varphi$ is invariant in $S$, then $post(R^{-1}, \varphi)$ is invariant in $T$.  

![Diagram showing the process of optimizing compilation with proof generation and invariant propagation.](image)
Compiler Validation Methods

1. **Automated Test Generation** (E.g., Csmith [2011] and EMI [2014])
   - Must generate test programs AND test inputs for those programs
   - All the advantages and the disadvantages of testing

2. **Proving correctness** once and for all (E.g., CompCert [Leroy 2006])
   - I.e., establish the theorem: \( \forall P \forall i \ P(i) = compile(P)(i) \)
   - Requires considerable effort and expertise; best when designing compiler with its proof

3. **Translation Validation**: Proving correctness per program (E.g., TVOC [2005])
   - I.e., Given \( P \), establish the theorem \( \forall i \ P(i) = compile(P)(i) \)
   - A different heuristic per optimization; validator correctness becomes an issue