CompCert : C compilers you can *formally* trust

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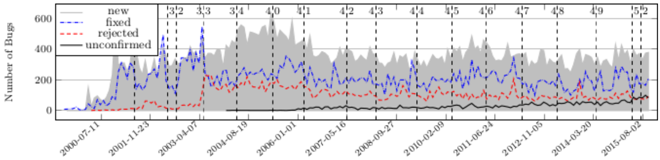
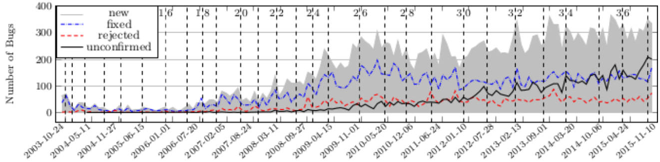
Contents

- Certifying compilers
- The Coq proof assistant for certifying compilers
- Using CompCert
- Overview of CompCert Implementation

Bug trackers of GCC and LLVM (Sun-et-al@PLDI'16)



(a) GCC.



(b) LLVM

The number of attested bugs tends to remain almost constant.
New bugs are introduced when compilers are improved !

Miscompilation bugs in most compilers (GCC, LLVM, etc)

Miscompilation bug $=$ incorrect generated code
$\neq$ "*performance*" bug in an optimization.

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Eide-Regehr'08, Yang-et-al'11, Lidbury-et-al'15, Sun-et-al'16...

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Optimizing compilers are quite large software (in MLoC)
with hundreds of maintainers, e.g :
`https://github.com/gcc-mirror/gcc/blob/master/MAINTAINERS`

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Another fundamental reason :
Tests of ***optimizing*** *compilers* **cannot cover** all corner cases
because of a **combinatorial explosion**.

Issue : *optimizing* compiler for *safety-critical* software

Strong safety-critical requirements of
DO-178 (Avionics), ISO-26262 (Automotive), IEC-62279 (Railway), IEC-61513 (Nuclear)
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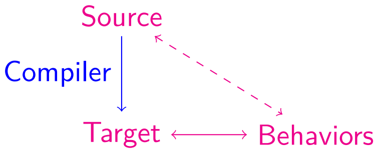
Better solution a *formally proved* compiler
for formal tool qualification (DO-178C + DO-333)...

Certified (= *formally proved*) compiler

Diagrammatic view
of the **correctness**



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Compiler

Target

Behaviors

Compiler correctness reduced to that of its formal spec.

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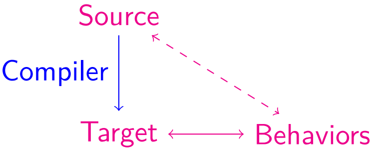

$$\begin{tikzcd}
\text{Source} \arrow[d, "\text{Compiler}"'] \arrow[dr, dashed, leftrightarrow] & \\
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\end{tikzcd}$$

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Advantages of formal spec over compiler code

- closer to informal spec (e.g. simpler for human reviews)
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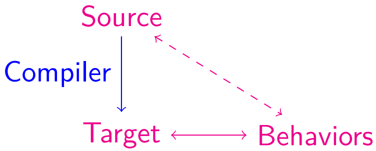

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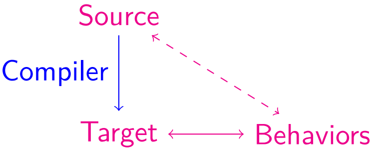

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Another benefit : traceability
formal proof = computer-aided review of the compiler code w.r.t its spec.
⇒ up-to-date & very sharp (formal) documentation of the compiler
that may also help "*external developers*"

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Part of an **ongoing effort to certify a whole software chain** in the COQ proof assistant
from the prover (e.g. CertiCoq) to OS kernels (e.g. CertiKOS)
Example `http://deepspec.org` (supported by NSF).

Contents

The COQ proof assistant

A *language* to **formalize mathematical theories** (and their proofs) **with a computer**. Examples :

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With a high-level of confidence :

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  Proofs checked by a small verifiable *kernel*
- Consistency-by-construction of most user theories
  (promotes *definitions* instead of *axioms*)

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Results from a long history in formalizing mathematical reasonning since Frege, Russel, Hilbert near 1900.

Formally proved programs in the Coq proof assistant

The Coq logic includes a functional programming language with pattern-matching on tree-like data-structures.

Extraction of Coq functions to OCaml
+ OCaml compilation to produce native code.

⇒ **CompCert is programmed in both Coq and OCaml.**

The kernel of Coq in a nutshell (1/2)

A *typed* programming language, *only* handling data of the form

- inductive data (tree-like data)
- (pure) functions (with structural recursion)
- types, where `Type`$_i$ is the type of `Type`$_j$ with $j < i$

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Example where `Z` in `Type`$_0$ is the type of relative integers

```
Inductive nat: Type := O | S(n:nat).  (* defines natural numbers *)

Fixpoint plus (n m:nat): nat :=       (* defines n+m recursively *)
  match n with O => m | (S n') => (S (plus n' m)) end.

(* Type of tuples containing (S n) values in Z *)
Fixpoint tuple_S (n:nat): Type :=
  match n with O => Z | S n' => Z * (tuple_S n') end.

(* Concatenation operation of such tuples *)
Fixpoint app (n m:nat):(tuple_S n)->((tuple_S m)->(tuple_S (S (plus n m)))) :=
  match n with
    O => fun t1 t2 => (t1, t2)
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Decidable typechecking with *computations in types*!

Only *structural* recursion is allowed ⇒ all computations terminates.

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Type of `app` :

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Typing rule : when `A:Type` (with restrictions) and `P: A->Type`$_i$
then `forall (x:A),(P x)` in `Type`$_i$

Propositions as types (Curry-Howard isomorphism)

`Prop` in $\texttt{Type}_1$ represents the type of *logical propositions* :
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Gives a *subset* of classical logic called *intuitionistic logic*.
Classical logic recovered with a few additional axioms like

```
Axiom excluded_middle: forall (A:Prop), A \/ (A -> False).
```

A flavour of certifying compilers in Coq

CompCert proof is huge ($>$ 100Kloc of Coq).

Follow this link to have a simpler example :
`http://www-verimag.imag.fr/~boulme/IntroCompCert/DemoCoq/`

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Input most of ISO C99 + a few extensions
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Performance of generated code (for PowerPC and ARM)

 2× *faster* than `gcc -O0`
 10% *slower* than `gcc -O1` and 20% than `gcc -O3`.

In MTU systems (German provider of Nuclear Power Plants)
28% *smaller* WCET than with a previous *unverified* compiler.

Understanding the formal correctness of COMPCERT

Formally, correctness of compiled code is ensured modulo

- correctness of C formal semantics in COQ
- correctness of assembly formal semantics in COQ
- absence of undefined behavior in the source program

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Source program assumed to be without undefined behavior

```
int x, t[10], y;
...
if (...) {
  t[10]=1; // undefined behavior: out of bounds
  // the compiler could write in x or y,
  // or prune the branch as dead-code, ...
```

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Behavior = one of the four possible cases (of an execution) :

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NB : under these conditions, C has no UNDEFINED-BEHAVIOR.

Trust in ELF binaries produced with CompCert

Trust in binaries requires additional verifications, at least :

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- correctness of assembling/linking (e.g. with Valex)

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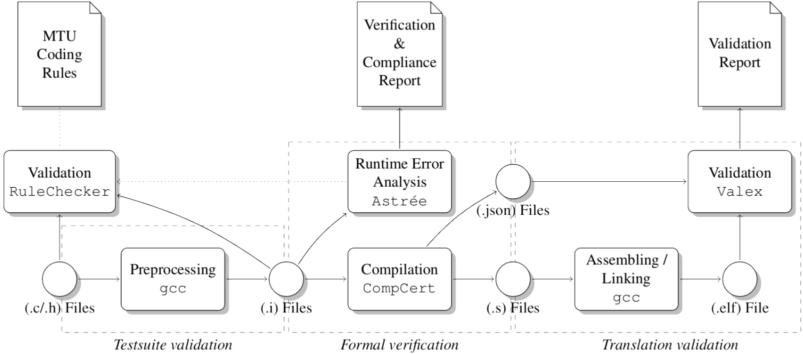

Qualification of MTU *development chain* for Nuclear safety
from Käster, Barrho et al @ERTS'18

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CompCert's model of Intermediate Representations

Definition The transition semantics (of a program) is defined – on a given type of states – by :

- a subset of initial states (i.e. at "`main`" entry-point) ;
- a subset of final states (i.e. at "`returns`" of "`main`") ;
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4 kind of behaviors recovered by :

- infinite sequence with a finite or infinite trace
- finite sequence ended on a final state
- finite sequence ended on a non-final state (*stuck*)

  ⇒ UNDEFINED-BEHAVIOR

Certifying compilation passes in CompCert

Theorem : correctness of forward simulations

The *correctness* of a pass between a *source semantics* on S_1 to a *deterministic target semantics* on S_2, can be proved by a simulation relation $S_1 \sim S_2$ that :

- is established on initial states
- preserves final states
- and execution steps with :

$$\begin{tikzcd}
S_1 \arrow[r, dash, "\sim"] \arrow[d, "t"'] & S_2 \arrow[d, dashed, "t"', "+"] \\
S'_1 \arrow[r, dash, dashed, "\sim"] & S'_2
\end{tikzcd}$$

or

$$\begin{tikzcd}
S_1 \arrow[r, dash, "\sim"] \arrow[d, "\epsilon"'] & S_2 \arrow[dl, dash, dashed, "\sim"'] \\
S'_1 &
\end{tikzcd}$$

with $|S'_1| < |S_1|$

NB : condition $|S'_1| < |S_1|$ ensures preservation of infinite silent loops.

Untrusted Oracles in CompCert

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- finding a *correct* and *efficient* allocation is difficult
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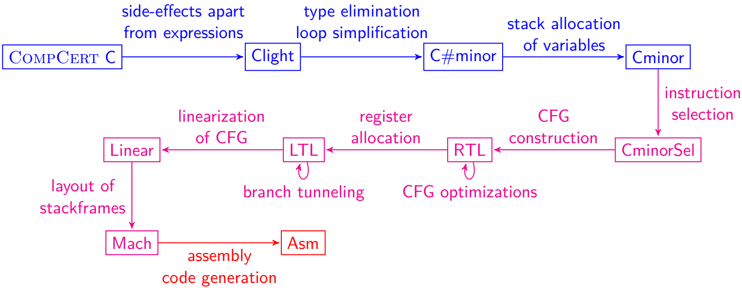
Benefits of untrusted oracles

simplicity + efficiency + modularity

Modular design of CompCert in Coq

Components independent/parametrized/specific w.r.t. the target



CompCert C → Clight: side-effects apart from expressions

Clight → C#minor: type elimination, loop simplification

C#minor → Cminor: stack allocation of variables

Cminor → CminorSel: instruction selection

CminorSel → RTL: CFG construction

RTL → RTL: CFG optimizations

RTL → LTL: register allocation

LTL → LTL: branch tunneling

LTL → Linear: linearization of CFG

Linear → Mach: layout of stackframes

Mach → Asm: assembly code generation

Modular design of CompCert in Coq

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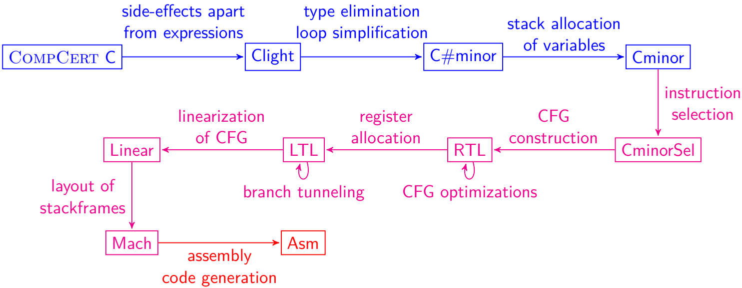

Demo on a mini example for x86-64 target at this link :
`http://www-verimag.imag.fr/~boulme/IntroCompCert/DemoCompCert/`