Compiler verification for fun and profit

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Prologue:
Can you trust your compiler?

The compilation process

General definition: any automatic translation from a computer language to another.

Restricted definition: efficient ("optimizing") translation from a source language (understandable by programmers) to a machine language (executable in hardware).

A mature area of computer science:

- Nearly 60 years old! (Fortran I: 1957)
- Huge corpus of code generation and optimization algorithms.
- Many industrial-strength compilers that perform subtle transformations.

An example of compiler optimization

Consider:

```
double dotproduct(int n, double * a, double * b)
{
    double dp = 0.0;
    int i;
    for (i = 0; i < n; i++) dp += a[i] * b[i];
    return dp;
}
```

Compiled with the Tru64/Alpha compiler and manually decompiled back to C. . .

```
double dotproduct(int n, double a[], double b[]) {
     dp = 0.0;
     if (n <= 0) goto L5;
     r2 = n - 3; f1 = 0.0; r1 = 0; f10 = 0.0; f11 = 0.0;
     if (r2 > n || r2 <= 0) goto L19;
     prefetch(a[16]); prefetch(b[16]);
     if (4 >= r2) goto L14;
     prefetch(a[20]); prefetch(b[20]);
     f12 = a[0]; f13 = b[0]; f14 = a[1]; f15 = b[1];
     r1 = 8; if (8 >= r2) goto L16;
L17: f16 = b[2]; f18 = a[2]; f17 = f12 * f13;
     f19 = b[3]; f20 = a[3]; f15 = f14 * f15;
     f12 = a[4]; f16 = f18 * f16;
     f19 = f29 * f19; f13 = b[4]; a += 4; f14 = a[1];
     f11 += f17; r1 += 4; f10 += f15;
     f15 = b[5]; prefetch(a[20]); prefetch(b[24]);
     f1 += f16; dp += f19; b += 4;
     if (r1 < r2) goto L17;
L16: f15 = f14 * f15; f21 = b[2]; f23 = a[2]; f22 = f12 * f13;
     f24 = b[3]; f25 = a[3]; f21 = f23 * f21;
     f12 = a[4]; f13 = b[4]; f24 = f25 * f24; f10 = f10 + f15;
     a += 4; b += 4; f14 = a[8]; f15 = b[8];
     f11 += f22; f1 += f21; dp += f24;
L18: f26 = b[2]; f27 = a[2]; f14 = f14 * f15;
     f28 = b[3]; f29 = a[3]; f12 = f12 * f13; f26 = f27 * f26;
     a += 4; f28 = f29 * f28; b += 4;
     f10 += f14; f11 += f12; f1 += f26;
     dp += f28;  dp += f1; dp += f10; dp += f11;
     if (r1 >= n) goto L5;
L19: f30 = a[0]; f18 = b[0]; r1 += 1; a += 8; f18 = f30 * f18; b += 8;
     dp += f18;
     if (r1 < n) goto L19;
L5:  return dp;
L14: f12 = a[0]; f13 = b[0]; f14 = a[1]; f15 = b[1]; goto L18;
}
```

```
L17: f16 = b[2]; f18 = a[2]; f17 = f12 * f13;
     f19 = b[3]; f20 = a[3]; f15 = f14 * f15;
     f12 = a[4]; f16 = f18 * f16;
     f19 = f29 * f19; f13 = b[4]; a += 4; f14 = a[1];
     f11 += f17; r1 += 4; f10 += f15;
     f15 = b[5]; prefetch(a[20]); prefetch(b[24]);
     f1 += f16; dp += f19; b += 4;
     if (r1 < r2) goto L17;
```

```
double dotproduct(int n, double a[], double b[]) {
    dp = 0.0;
    if (n <= 0) goto L5;
    r2 = n - 3; f1 = 0.0; r1 = 0; f10 = 0.0; f11 = 0.0;
    if (r2 > n || r2 <= 0) goto L19;
    prefetch(a[16]); prefetch(b[16]);
    if (4 >= r2) goto L14;
    prefetch(a[20]); prefetch(b[20]);
    f12 = a[0]; f13 = b[0]; f14 = a[1]; f15 = b[1];
    r1 = 8; if (8 >= r2) goto L16;









L16: f15 = f14 * f15; f21 = b[2]; f23 = a[2]; f22 = f12 * f13;
    f24 = b[3]; f25 = a[3]; f21 = f23 * f21;
    f12 = a[4]; f13 = b[4]; f24 = f25 * f24; f10 = f10 + f15;
    a += 4; b += 4; f14 = a[8]; f15 = b[8];
    f11 += f22; f1 += f21; dp += f24;
L18: f26 = b[2]; f27 = a[2]; f14 = f14 * f15;
    f28 = b[3]; f29 = a[3]; f12 = f12 * f13; f26 = f27 * f26;
    a += 4; f28 = f29 * f28; b += 4;
    f10 += f14; f11 += f12; f1 += f26;
    dp += f28;  dp += f1; dp += f10; dp += f11;
    if (r1 >= n) goto L5;
L19: f30 = a[0]; f18 = b[0]; r1 += 1; a += 8; f18 = f30 * f18; b += 8;
    dp += f18;
    if (r1 < n) goto L19;
L5:  return dp;
L14: f12 = a[0]; f13 = b[0]; f14 = a[1]; f15 = b[1]; goto L18;
}
```

Even unoptimized code generation is delicate

```
double floatofint(unsigned int i) { return (double) i; }
```

The PowerPC 32-bit architecture provides no instruction to convert from int to float. The compiler must therefore emulate it, as follows:

```
double floatofint(unsigned int i)
{
    union { double d; unsigned int x[2]; } u, v;
    u.x[0] = 0x43300000;   u.x[1] = i;
    v.x[0] = 0x43300000;   v.x[1] = 0;
    return u.d - v.d;
}
```

(Hint: the 64-bit integer `0x43300000` $\times 2^{32} + x$ is the IEEE754 encoding of the double float $2^{52} +$ (`double`)x.)

Miscompilation happens

NULLSTONE isolated defects [in integer division] in twelve of twenty commercially available compilers that were evaluated.

`http://www.nullstone.com/htmls/category/divide.htm`

We tested thirteen production-quality C compilers and, for each, found situations in which the compiler generated incorrect code for accessing volatile variables. This result is disturbing because it implies that embedded software and operating systems — both typically coded in C, both being bases for many mission-critical and safety-critical applications, and both relying on the correct translation of volatiles — may be being miscompiled.

E. Eide & J. Regehr, EMSOFT 2008

Miscompilation happens

We created a tool that generates random C programs, and then spent two and a half years using it to find compiler bugs. So far, we have reported more than 325 previously unknown bugs to compiler developers. Moreover, every compiler that we tested has been found to crash and also to silently generate wrong code when presented with valid inputs.

X. Yang, Y. Chen, E. Eide, J. Regehr, PLDI 2011

Latest sighting

[Our] new method succeeded in finding bugs in the latter five (newer) versions of GCCs, in which the previous method detected no errors.

```
int main (void)
{
  unsigned x = 2U;
  unsigned t = ((unsigned) -(x/2)) / 2;
  assert ( t != 2147483647 );
}
```

It turned out that [the program above] caused the same error on the GCCs of versions from at least 3.1.0 through 4.7.2, regardless of targets and optimization options.

E. Nagai, A. Hashimoto, N. Ishiura, SASIMI 2013

Are miscompilation bugs a problem?

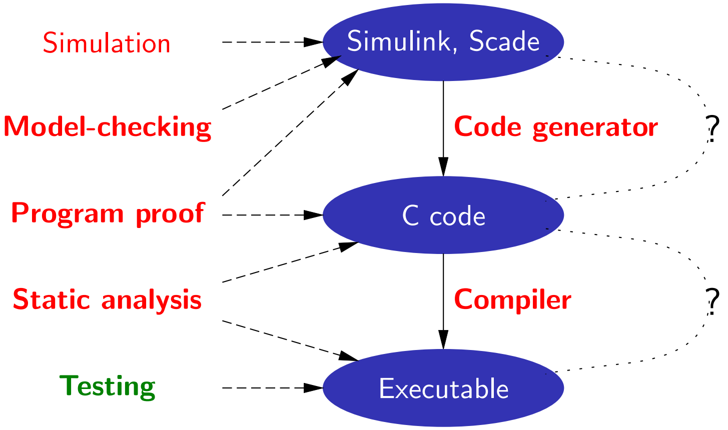
For non-critical software:

- Programmers rarely run into them.
- When they do, it's very hard to debug.
- Globally negligible compared with bugs in the program itself.

For critical software:

- A source of concern.
- Require additional verification activities.
  (E.g. manual reviews of generated assembly code; more tests.)
- Complicate the qualification process.
- Reduce the usefulness of formal verification.

Miscompilation and formal verification



The guarantees obtained (so painfully!) by source-level formal verification may not carry over to the executable code . . .

A solution? Verified compilers

Why not formally verify the compiler itself?

After all, compilers have simple specifications:

> *If compilation succeeds, the generated code should behave as prescribed by the semantics of the source program.*

As a corollary, we obtain:

> *Any safety property of the observable behavior of the source program carries over to the generated executable code.*

Compiler verification for profit

In the context of high-assurance software that undergoes strict certification (DO-178 in avionics, Common Criteria in security):

- Provides strong guarantees on compilers and code generators, guarantees that are very hard to obtain by more conventional methods (tests and reviews).
- Enable the use of aggressive optimizations (which would otherwise be problematic for certification).
- Generate confidence in the results of source-level formal verifications (making it easier to derive certification credit from these verifications).

Compiler verification for fun

Compilers are challenging pieces of software from a formal verification standpoint:

- Complex data structures: abstract syntax trees, control-flow graphs.
- Complex algorithms, often recursive.
- Specifications involve formal, operational semantics for "big" languages.

Beyond the reach of automated verification techniques?
(model checking, static analysis, automated deductive program provers).

A very good match for interactive theorem proving!

An old idea. . .

John McCarthy
James Painter[1]

CORRECTNESS OF A COMPILER FOR ARITHMETIC EXPRESSIONS[2]

1. **Introduction.** This paper contains a proof of the correctness of a simple compiling algorithm for compiling arithmetic expressions into machine language.

The definition of correctness, the formalism used to express the description of source language, object language and compiler, and the methods of proof are all intended to serve as prototypes for the more complicated task of proving the correctness of usable compilers. The ultimate goal, as outlined in references [1], [2], [3] and [4] is to make it possible to use a computer to check proofs that compilers are correct.

Mathematical Aspects of Computer Science, 1967

An old idea. . .

3

Proving Compiler Correctness in a Mechanized Logic

R. Milner and R. Weyhrauch
Computer Science Department
Stanford University

Abstract
We discuss the task of machine-checking the proof of a simple compiling algorithm. The proof-checking program is LCF, an implementation of a logic for computable functions due to Dana Scott, in which the abstract syntax and extensional semantics of programming languages can be naturally expressed. The source language in our example is a simple ALGOL-like language with assignments, conditionals, whiles and compound statements. The target language is an assembly language for a machine with a pushdown store. Algebraic methods are used to give structure to the proof, which is presented only in outline. However, we present in full the expression-compiling part of the algorithm. More than half of the complete proof has been machine checked, and we anticipate no difficulty with the remainder. We discuss our experience in conducting the proof, which indicates that a large part of it may be automated to reduce the human contribution.

Machine Intelligence (7), 1972.

CompCert:
a compiler you can formally trust

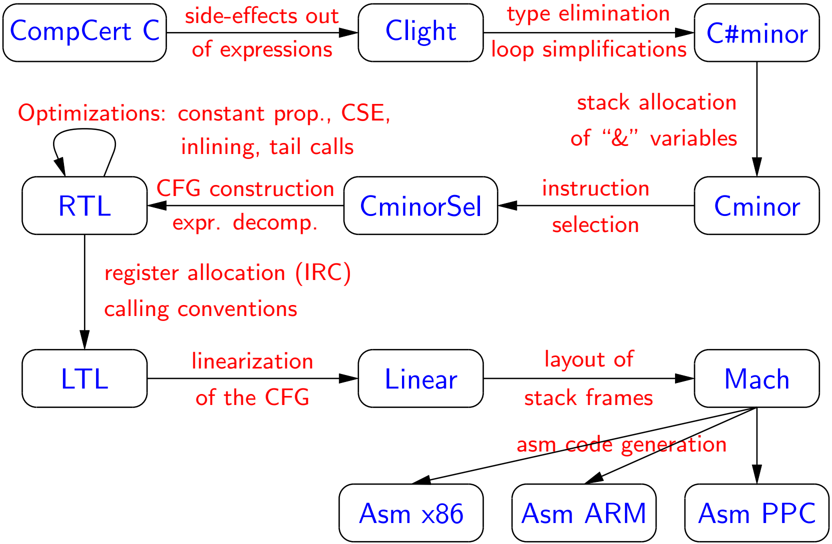
The CompCert project
(X.Leroy, S.Blazy, et al)

Develop and prove correct a realistic compiler, usable for critical embedded software.

- Source language: a very large subset of C99.
- Target language: PowerPC/ARM/x86 assembly.
- Generates reasonably compact and fast code
  $\Rightarrow$ careful code generation; some optimizations.

Note: compiler written from scratch, along with its proof; not trying to prove an existing compiler.

The formally verified part of the compiler



Formally verified using Coq

The correctness proof (semantic preservation) for the compiler is entirely machine-checked, using the Coq proof assistant.

```
Theorem transf_c_program_preservation:
  forall p tp beh,
  transf_c_program p = OK tp ->
  program_behaves (Asm.semantics tp) beh ->
  exists beh', program_behaves (Csem.semantics p) beh'
          /\ behavior_improves beh' beh.
```

What does semantic preservation say?

Behaviors `beh` =

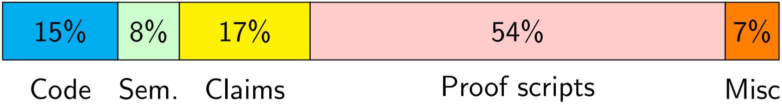
termination / divergence / crashing on an undefined behavior
+ trace of I/O operations (system calls & volatile accesses)

The theorem says that the behavior of the generated code is at least as good as one of the behaviors of the source program:

Source code:	$i_1.o_1.o_2.i_2.o_3$	$i_1.o_1.\dagger$ undefined behavior
Compiled code:	$i_1.o_1.o_2.i_2.o_3$	$i_1.o_1.o_2\ldots$
	(same behavior)	("improved" undefined behavior)

If the source code was verified to be free of undefined behaviors, we know that the compiled code behaves exactly like the source program.

Proof effort



100,000 lines of Coq.

Including 15000 lines of “source code” ($\approx$ 60,000 lines of Java).

6 person.years

Low proof automation (could be improved).

Programmed (mostly) in Coq

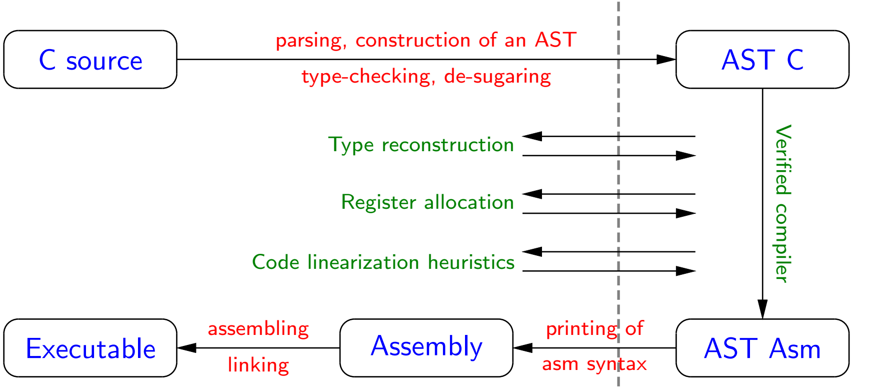
All the verified parts of the compiler are programmed directly in Coq's specification language, using pure functional style.

- Monads to handle errors and mutable state.
- Purely functional data structures.

Coq's extraction mechanism produces executable Caml code from these specifications.

Claim: purely functional programming is the shortest path to writing and proving a program.

The whole Compcert compiler



Part of the TCB

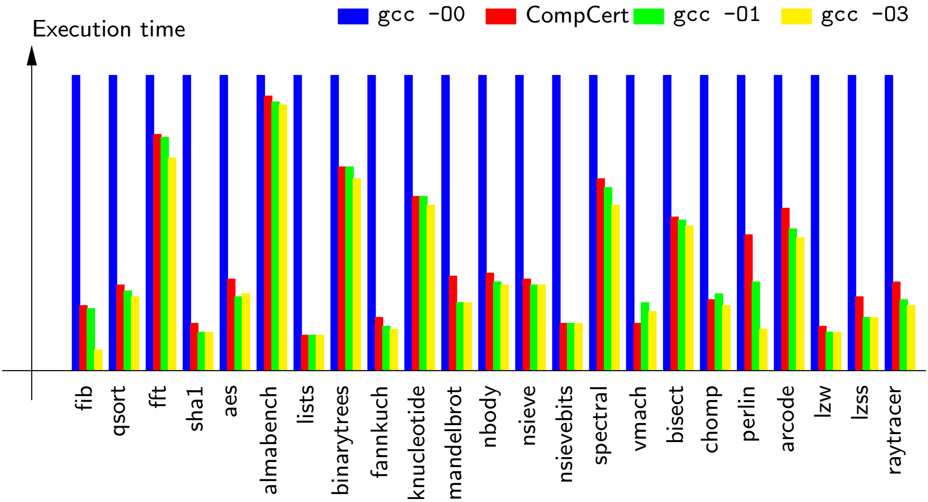
Not part of the TCB

Not proved
(hand-written in Caml)

Proved in Coq
(extracted to Caml)

Performance of generated code

(On a Power 7 processor)



A tangible increase in quality

The striking thing about our CompCert results is that the middleend 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.

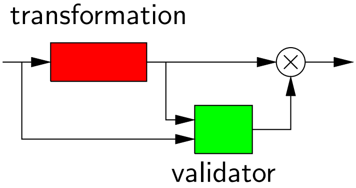
X. Yang, Y. Chen, E. Eide, J. Regehr, PLDI 2011

A peek under the hood: how to verify a compilation pass

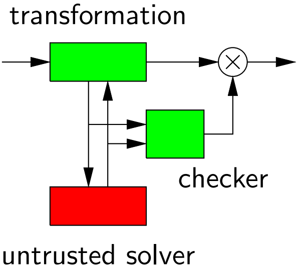
Compiler verification patterns (for each pass)

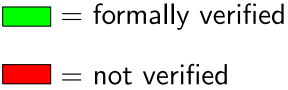
Verified transformation

Verified translation validation



External solver with verified validation





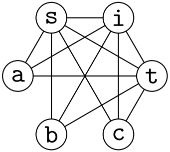
Verified transformation vs. verified validation

Verified validation: usually less to prove; sound; may fail at compile-time.
Verified transformation: usually more to prove; sound; complete.

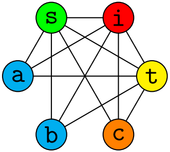
Example: register allocation via graph coloring.

```
a = i << 2
b = load(t+a)
c = float(b)
s = s + c
```

liveness analysis
constr. interf. graph



graph coloring



code rewriting
insert spill code

```
R3 = R2 << 2
R3 = load(R1+R3)
F1 = float(R3)
F2 = reload(SP+16)
F2 = F2 + F1
spill(F2, SP+16)
```

The verified-validated continuum

(May fail)

Not proved

Graph coloring
(IRC algorithm)

2600 LOC

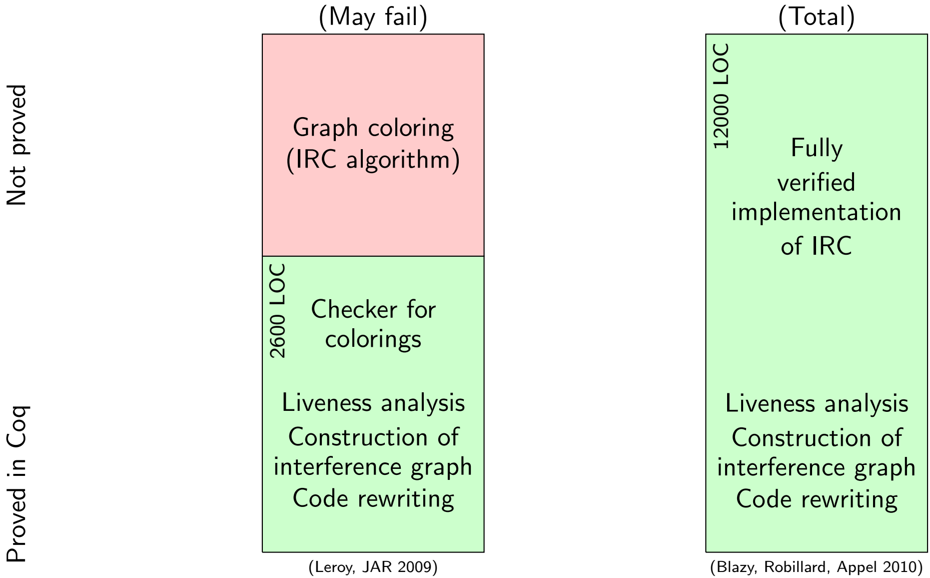
Checker for
colorings

Proved in Coq

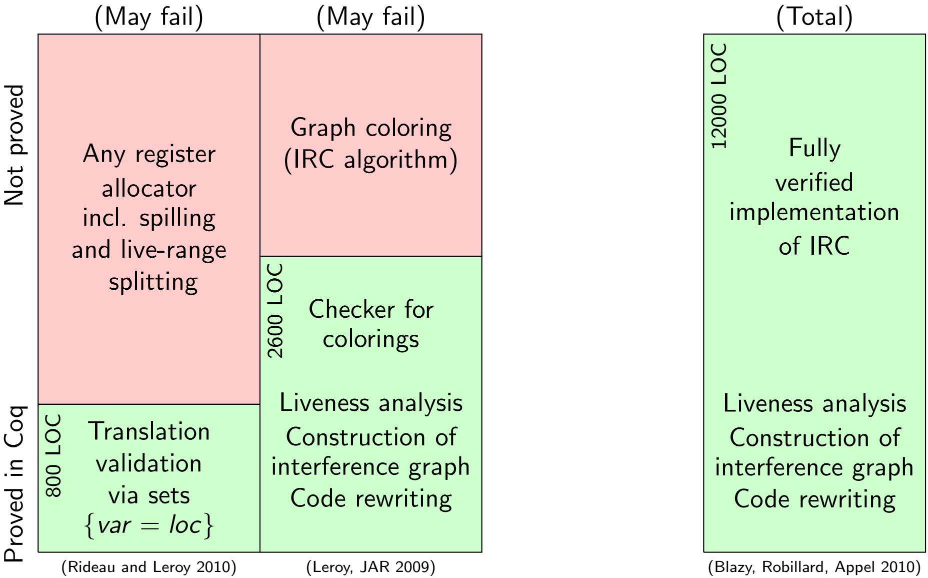
Liveness analysis
Construction of
interference graph
Code rewriting

(Leroy, JAR 2009)

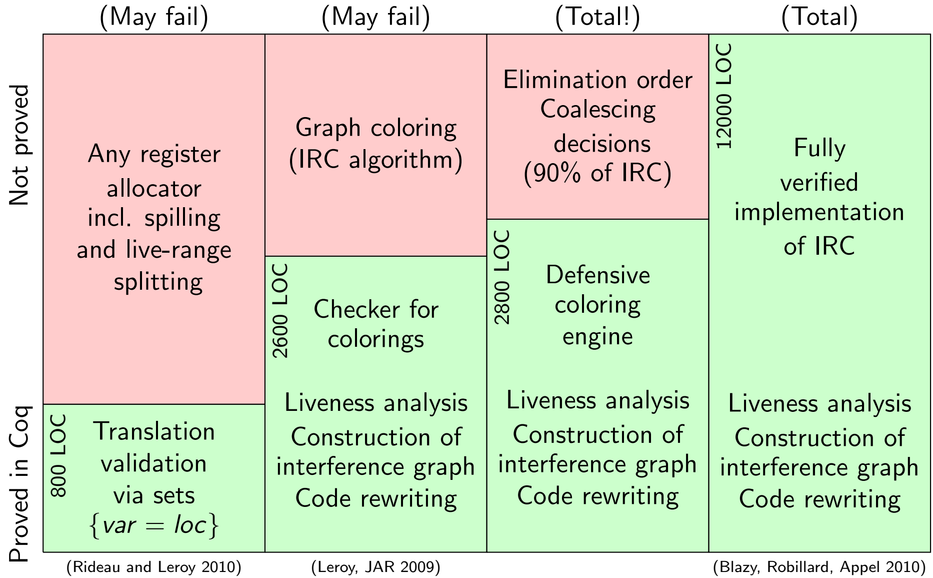
The verified-validated continuum



The verified-validated continuum



The verified-validated continuum



Validating register allocation a posteriori

(Silvain Rideau & Xavier Leroy, Compiler Construction 2010)

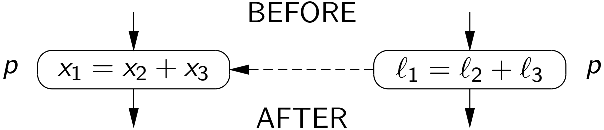
For each program point p, infer and check the consistency of a set of equations $E(p)$ between variables and locations (*):

$$E(p) = \{x_1 = \ell_1; \ldots; x_n = \ell_n\}$$

Intuition: in every execution of the original code and the transformed code, the current value of ℓ_i at p is the same as that of x_i at p.

(*) locations = processor registers $\cup$ stack slots.

Forward analysis



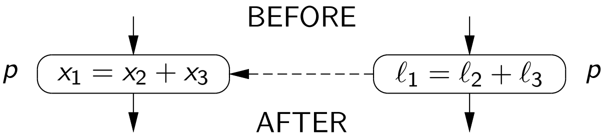
Assume given a set of equations `BEFORE` that holds “before” point p.

Check that $\{x_2 = \ell_2\} \in$ `BEFORE` and $\{x_3 = \ell_3\} \in$ `BEFORE`.

Compute set of equations `AFTER` that holds “after” points p:

- Remove all equations $x = \ell$ such that $x = x_1$ or ℓ overlaps with ℓ_1.
- Add equation $x_1 = \ell_1$

Alternative: backward analysis



Assume given a set of equations `AFTER` that must hold "after" point p for the rest of the executions to behave identically.

Check that `AFTER` contains no equations $x = \ell$ such that
$(x, \ell) \neq (x_1, \ell_1)$ and ($x = x_1$ or ℓ overlaps with ℓ_1).
(These equations cannot be satisfied in general.)

Compute set of equations `BEFORE` that must hold "before" point p for the rest of the executions to behave identically:

- Remove the equation $x_1 = \ell_1$ if present.
- Add equations $x_2 = \ell_2$ and $x_3 = \ell_3$.

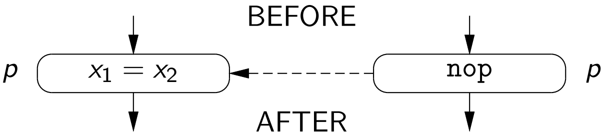
Comparing backward and forward approaches

If we project the sets of equations $\{x_i = \ell_i\}$ on one side, say $\{x_i\}$:

Equations inferred:	Forward approach	$\supseteq$	Backward approach
Projections:	Reaching definitions	$\supseteq$	Live variables

In general, the backward approach is more efficient because it produces smaller sets of equations.

Backward equations for coalesced copies

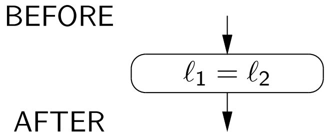


Assume given a set of equations `AFTER` that must hold "after" point p for the rest of the executions to behave identically.

The set `BEFORE` of equations that must hold "before" is

$$\begin{array}{rl} & \{(x_2 = \ell) \mid (x_1 = \ell) \in \mathtt{AFTER}\} \\ \cup & \{(x = \ell) \mid (x = \ell) \in \mathtt{AFTER} \text{ and } x \neq x_1\} \end{array}$$

Backward equations for inserted moves



Check that `AFTER` contains no equation $x = \ell$ with $\ell \neq \ell_1$ and ℓ overlaps ℓ_1.

The set `BEFORE` of equations that must hold "before" is

$$\begin{array}{ll} & \{(x = \ell_2) \mid (x = \ell_1) \in \texttt{AFTER}\} \\ \cup & \{(x = \ell) \mid (x = \ell) \in \texttt{AFTER} \text{ and } \ell \neq \ell_1\} \end{array}$$

The validation algorithm

$\texttt{check\_function}(f, f') =$

compute the solutions $E(p)$ of the dataflow equations

$$E(p) = \bigcup \{\texttt{transfer}(f, f', s', E(s') \mid s' \text{ successor of } p \text{ in } f\}$$

let $E_0 = \texttt{transfer}(f, f', f'.\texttt{entrypoint}, E(f'.\texttt{entrypoint}))$

check $E_0 \neq \top$ and

$$E_0 \cap f.\texttt{params} \subseteq \{f.\texttt{params} = \texttt{parameters}(f'.\texttt{typesig})\}$$

Soundness proof

Theorem: if $\texttt{check\_function}(f, f') = \texttt{true}$, the transformed function f' behaves at run-time exactly like f.

The proof builds on a forward simulation diagram:

$$
\begin{tikzcd}
(p_1, e_1, m_1) \arrow[r, dash, "e_1, e'_1 \models \texttt{BEFORE}(p_1)"] \arrow[d] & (p_1, e'_1, m_1) \arrow[d, dashed, "+"] \\
(p_2, e_2, m_2) \arrow[r, dash, dashed, "e_2, e'_2 \models \texttt{BEFORE}(p_2)"'] & (p_2, e'_2, m_2)
\end{tikzcd}
$$

Satisfaction of a set E of equations by a state e : *variable* $\rightarrow$ *value* and a state e' : *location* $\rightarrow$ *value*:

$$e, e' \models E \overset{\text{def}}{=} \forall (x = \ell) \in E,\ x \in \mathrm{Dom}(e) \Longrightarrow e(x) = e'(\ell)$$

Semantic preservation for whole executions

$$
\begin{tikzcd}
\text{(initial state)} & S_1 \arrow[r, dash, "\textit{invariant}"] \arrow[d, "\epsilon"'] & T_1 \arrow[d, "\epsilon"] & \text{(initial state)} \\
 & S_2 \arrow[r, dash, "\textit{invariant}"'] \arrow[d, "\nu_1"'] & T_2 \arrow[d, "\nu_1"] & \\
 & S_3 \arrow[r, dash, "\textit{invariant}"'] \arrow[d, "\nu_2"'] & T_3 \arrow[d, "\nu_2"] & \\
 & S_4 \arrow[r, dash, "\textit{invariant}"'] \arrow[d, "\epsilon"'] & T_4 \arrow[d, "\epsilon"] & \\
\text{(final state)} & S_5 \arrow[r, dash, "\textit{invariant}"'] & T_5 & \text{(final state)}
\end{tikzcd}
$$

Proves that the original program and the transformed program have the same behavior (the trace $t = \nu_1.\nu_2$).

Towards other source languages

Verified compilation of various languages

High-level, garbage-collected languages (Java, C#, functional)

C++

C

Scripting languages (Javascript)

Domain-specific languages (hardware description, synchronous/reactive, query languages, etc)

C: the *lingua franca* of systems programming

– low-level semantics with many dark corners

+ relatively simple compilation (but: optimization is difficult)

+ no run-time system

Verified compilation of various languages

High-level,
garbage-collected
languages
(Java, C#, functional)

C++

C

Scripting languages
(Javascript)

Domain-specific languages
(hardware description,
synchronous/reactive,
query languages, etc)

C++:
– all the dark corners of C plus a complex object model
+ C-like compilation
– a bit of a run-time system (exceptions)

Verified compilation of various languages

High-level,
garbage-collected
languages
(Java, C#, functional)

C++

C

Scripting languages
(Javascript)

Domain-specific languages
(hardware description,
synchronous/reactive,
query languages, etc)

High-level garbage-collected languages:
+ clean semantics
+ nontrivial but interesting compilation
– large run-time system (allocation, GC, exceptions, . . .)

Verified compilation of various languages

High-level,
garbage-collected
languages
(Java, C#, functional)

C++

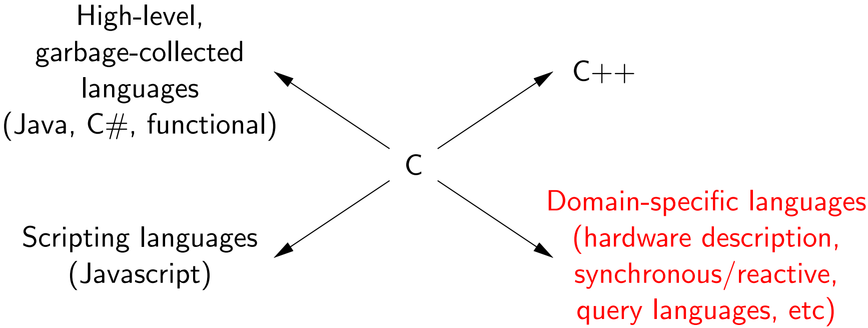
C

Scripting languages
(Javascript)

Domain-specific languages
(hardware description,
synchronous/reactive,
query languages, etc)

Scripting languages:
– obscure semantics
– not designed for compilation
– very large run-time system (GC + DOM + . . .)

Verified compilation of various languages



Domain-specific languages with limited expressiveness:

\+ clean semantics

\+ opportunities for superoptimization & synthesis

\+ no run-time system

\+ used in critical embedded systems (e.g. Scade, Simulink)

FeSi (Featherweight Synthesis): verified hardware synthesis

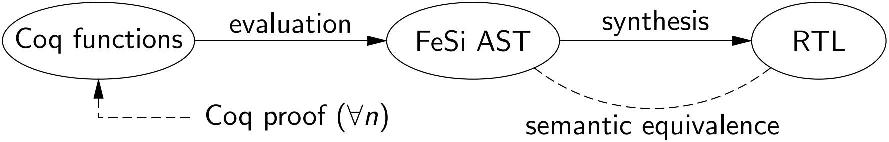
(Thomas Braibant & Adam Chlipala, CAV'13)

A simple, declarative hardware description language in the style of Lava and Bluespec.

Oriented towards the description and proof of parameterized circuits (e.g. n-bit multiplier for all n).

Embedded within Coq $\rightarrow$ dependent types, recursion, ...

Simple but nontrivial synthesis of RTL circuits, verified in Coq.



A taste of FeSi: *n*-bit carry-lookahead adder (simplified)

```
Fixpoint add {Phi} n (x : expr V (Tint [2^n])) (y : expr V (Tint [2^n]))
: action Phi V (Ttuple [Tbool; Tbool; Tint [2^n]; Tint [2^n]]) :=
  match n with
  | 0 =>
      ret [tuple ((x = #i 1) || (y = #i 1)), (* propagated carry *)
                 ((x = #i 1) && (y = #i 1)), (* generated carry *)
                 x + y,                      (* sum if no carry-in *)
                 x + y + #i 1 ]              (* sum if carry-in *)
  | S n =>
      do xL <~ low x; do xH <~ high x; do yL <~ low y; do yH <~ high y;
      do rL <- add n xL yL; do rH <- add n xH yH;
      do (pL, gL, sL, tL) <~ rL; do (pH, gH, sH, tH) <~ rH;
      do sH' <~ (Emux (gL) (tH) (sH));
      do tH' <~ (Emux (pL) (tH) (sH));
      do pH' <~ (gH || (pH && pL));
      do gH' <~ (gH || (pH && gL));
      ret [tuple pH', gH', combineLH sL sH', combineLH tL tH']
  end
```

Note: dependent types + recursion + circuit generation.

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A taste of FeSi: n-bit carry-lookahead adder (simplified)

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```

Note: dependent types + recursion + circuit generation.

FeSi internal representation

A type of expressions (= combinatorial circuits) . . .

```
Inductive expr: ty → Type :=
  (* Input wires *)
    | Evar : ∀ t, V t → expr t
  (* Operations on Booleans *)
    | Eandb : expr B → expr B → expr B | ...
  (* Operations on n-bit integers *)
    | Eadd : ∀ n, expr (Int n) → expr (Int n) → expr (Int n) | ...
  (* Operations on tuples *)
    | Efst : ∀ l t, expr (Tuple (t:: l)) → expr t | ...
```

FeSi internal representation

. . . and a type of actions (= sequential circuits).

```
Inductive action: ty → Type:=
    | Return: ∀ t, expr t → action t
  (* Connecting two actions via a wire *)
    | Bind: ∀ t u, action t → (V t → action u) → action u
  (* Guards (control flow) *)
    | Assert: expr B → action Unit
    | OrElse: ∀ t, action t → action t → action t
  (* Operations on registers *)
    | RegRead : ∀ t, member Φ (Reg t) → action t
    | RegWrite: ∀ t, member Φ (Reg t) → expr t → action Unit
```

High-level semantics: close to that of a functional language.
Register writes are batched and performed at end of cycle.
The semantics of an action is a state transformer

state at beginning of cycle → *state at beginning of next cycle*

Compiling FeSi to RTL

A simple 4-stage compiler with a few optimizations:

1. Normalization: give names to intermediate results.
2. Transform control-flow into data-flow;
   synthesize write-enable signals for register updates.
3. Syntactic common subexpression elimination.
4. BDD-based reduction of Boolean expressions.

Putting it all together

The FeSi compilation pipeline and its correctness statement:

```
Variable (Φ: list mem) (t : ty).

Definition fesic (A : Fesi. Action Φ t) : RTL.Block Φ t :=
  let x := IR. Compile Φ t a in
  let x := RTL.Compile Φ t x in
  let x := CSE.Compile Φ t x in
  BDD.Compile Φ t x.

Theorem fesic_correct :
  ∀ A (Γ : Φ ), Front.Next Γ A = RTL.Next Γ (fesic A).
```

In closing. . .

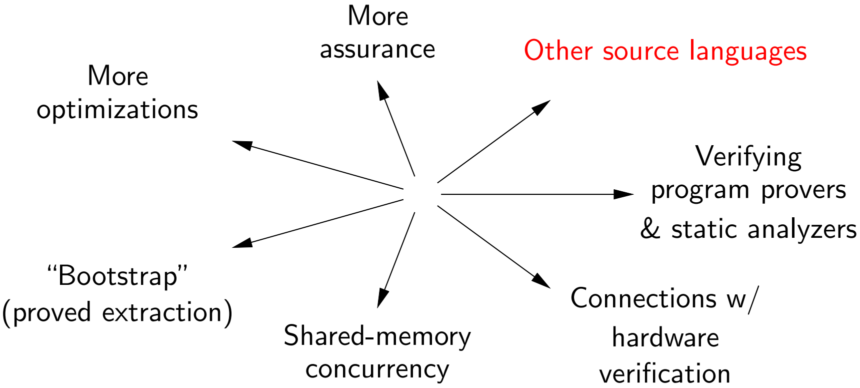
Current status

At this stage of the CompCert experiment, the initial goal — proving correct a nontrivial compiler — appears feasible.

(Within the limitations of today's proof assistants such as Coq.)

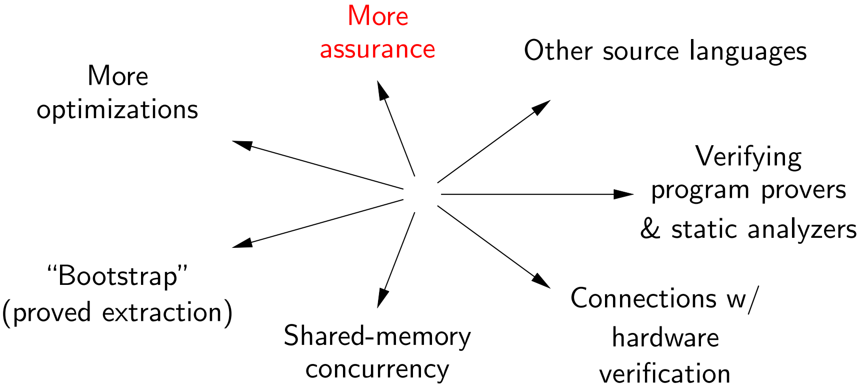
Towards industrialization (partnership with AbsInt Gmbh).

Some directions for future work



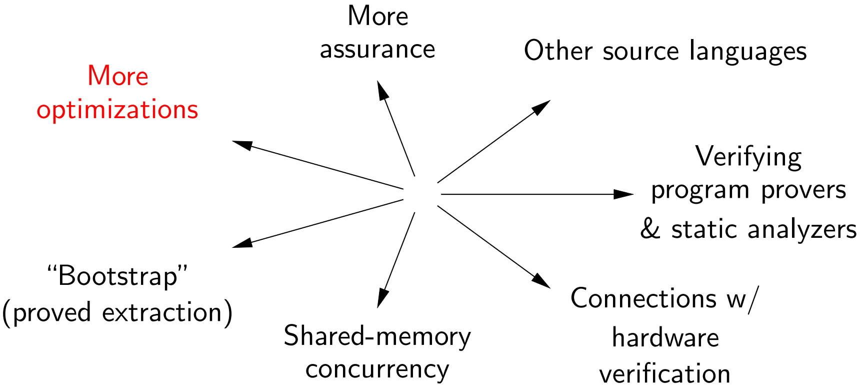
Other source languages besides C (already discussed).

Some directions for future work



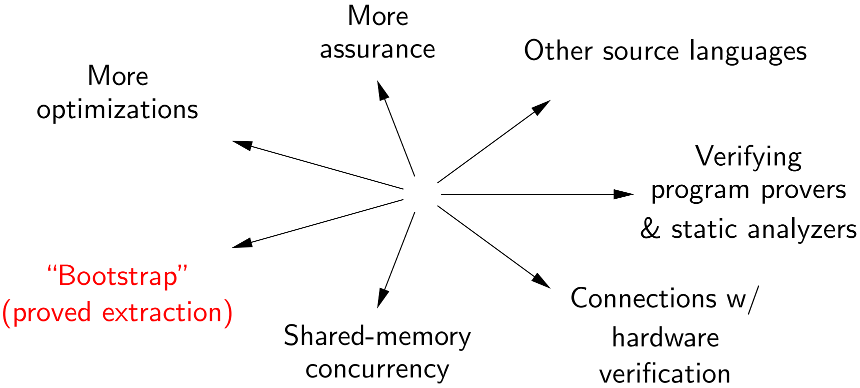
Prove or validate more of the TCB:
lexing, typing, elaboration, assembling, linking, ...

Some directions for future work



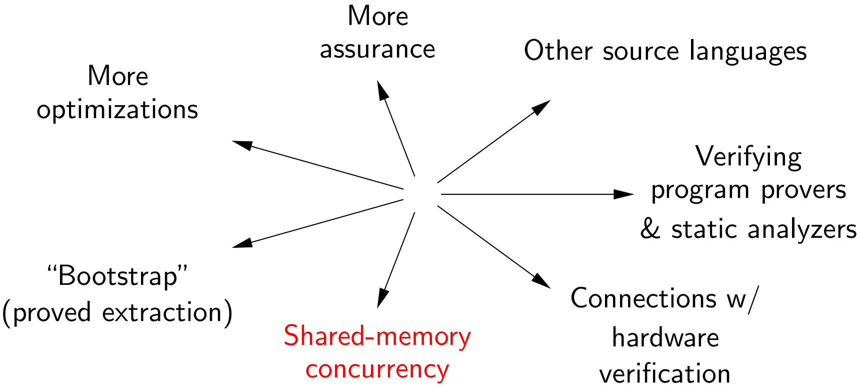
Add advanced optimizations, esp. loop optimizations.
Verified validation as the approach of least resistance.

Some directions for future work



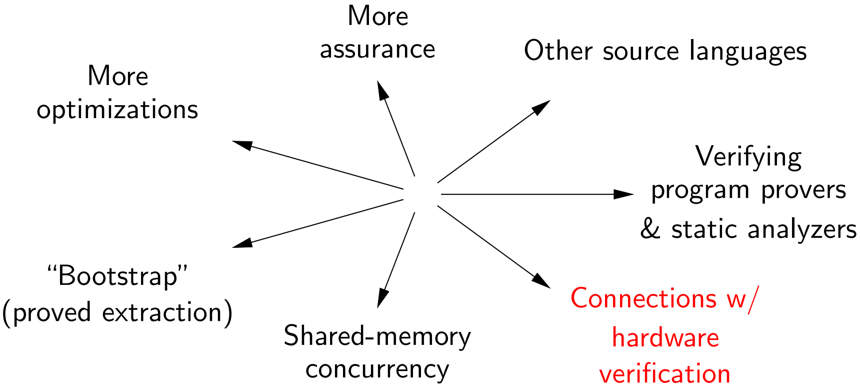
Increase confidence in the tools used to build CompCert:
Coq's extraction facility + the Caml compiler.

Some directions for future work



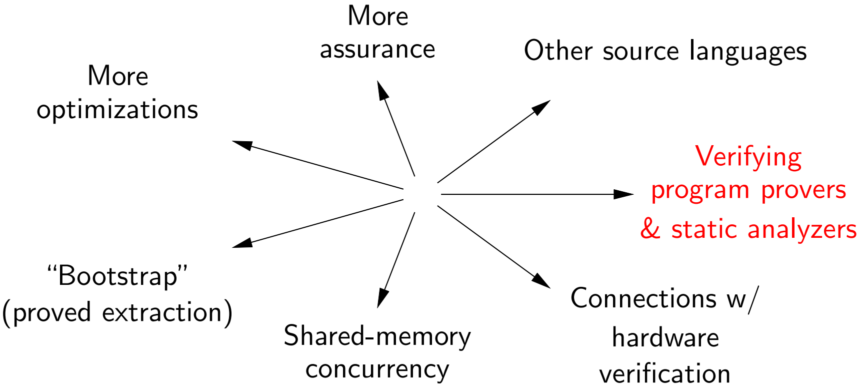
Race-free programs + concurrent separation logic (A. Appel et al)
or: racy programs + hardware memory models (P. Sewell et al).

Some directions for future work



Formal specs for architectures & instruction sets, as the missing link between compiler verification and hardware verification.

Some directions for future work



The Verasco project: formal verification of a static analyzer based on abstract interpretation. (Inria, Verimag, Airbus).

In closing...

Critical software deserves the most trustworthy tools that computer science can provide.

The formal verification of development and verification tools for critical software

- appears within reach,
- raises fascinating verification issues,
- improves our understanding of the algorithms involved,
- and could have practical impact.

For more information

http://compcert.inria.fr/

Research papers.

Complete source & proofs available for evaluation and research purposes.

Compiler runs on / produces code for
{Linux,MacOSX,Windows+Cygwin} / {PowerPC, ARM, x86}.