A Formally-Verified C Compiler Supporting Floating-Point Arithmetic

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Floating-Point Arithmetic and Optimizations

Example (FastTwoSum)

```c
double y, z;
y = 0x1p-53 + 0x1p-78; // y = 2^{-53} + 2^{-78} > \frac{1}{2}ulp(1)
z = ((1. + y) - 1.) - y;
printf("%a\n", z); // Dekker says: z = 2^{-53} - 2^{-78}
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General opinion

*From a practical perspective, preserving the “floating point” semantics is only interesting if not doing so will result in an execution error. That is, from a programmer’s perspective, playing “fast and loose” with floating semantics is generally OK if the resulting executable does what you want and runs fast.*

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Floating-Point Arithmetic and Compilers

Trivia

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Answer

Bug #323: “optimized code gives strange floating point results”.

Some people call this a bug in the x87 series. Other call it a bug in gcc. Regardless of where one wishes to put the blame, this problem will not be fixed. Period.

— GCC developer, 2005

Answer continued

109 duplicate bug-reports!

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What Can Users Expect From FP Arithmetic?

*Rounding takes a number regarded as infinitely precise and, if necessary, modifies it to fit in the destination’s format [...]. Every operation shall be performed as if it first produced an intermediate result correct to infinite precision and with unbounded range, and then rounded that result [...].*

— IEEE-754 2008
What Languages Say About FP Arithmetic

Java SE 7 (15.4 FP-strict expressions)
Within an expression that is not FP-strict, some leeway is granted for an implementation to use an extended exponent range to represent intermediate results.

C99 (5.2.4.2.2 Characteristics of floating types)
The values of operations with floating operands [...] are evaluated to a format whose range and precision may be greater than required by the type.

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How do avionics developers explain to a certification authority that their C programs are airworthy? (E.g. DO-178 regulations.)
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Answer
- They disable compiler optimizations.
- They read the assembly code generated by the C compiler.
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Trust in the compilers? Absolutely none.
How to Improve the Situation

Proposal

Build a C compiler that can be trusted and does not mess with floating-point code.
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Build a C compiler that can be trusted and does not mess with floating-point code.

Components

CompCert: a C compiler targeting ARM, PowerPC, x86-SSE2
- mathematical specification of the semantics of C and target,
- formal proof that compilation preserves semantics.
## Proposal

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## Components

**CompCert**: a C compiler targeting ARM, PowerPC, x86-SSE2
- mathematical specification of the semantics of C and target,
- formal proof that compilation preserves semantics.

**Flocq**: a Coq formalization of FP arithmetic
- multi-radix, multi-format, multi-precision arithmetic,
- comprehensive library, including computable operations.
Outline

1. Introduction
2. CompCert, a formally-verified compiler
3. Flocq, a Coq formalization of FP arithmetic
4. CompCert with floating-point support
5. Conclusion
Outline

1. Introduction

2. CompCert, a formally-verified compiler
   - Semantics preservation
   - Floating-point arithmetic in the earlier days

3. Flocq, a Coq formalization of FP arithmetic

4. CompCert with floating-point support

5. Conclusion
Semantics Preservation

**Theorem**

Let $S$ be a source C program free of undefined behaviors. Assume that the CompCert compiler, invoked on $S$, does not report a compile-time error, but instead produces executable code $E$. Then, any observable behavior $B$ of $E$ is one of the possible observable behaviors of $S$. 
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**Corollary**

You do not need to know how the compiler works, nor how the target environment behaves, in order to know what the produced executable will compute.
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**Implicit assumptions**

- The compiler behaves as proved.
- The target environment is correctly formalized.
Semantics Preservation

Semantics preservation guarantees that reading the semantics of the input language of the compiler is sufficient to understand how the programmer’s code will end up.
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Example (Clight semantics)

In the code:
```coq
Inductive step: state -> trace -> state -> Prop :=
  ... |
  step_seq: forall f s1 s2 k e le m,
    step (State f (Ssequence s1 s2) k e le m)
    E0 (State f s1 (Kseq s2 k) e le m)
...```

Disclaimer: it is painful (about 1000 lines of Coq), but not as painful as reading the code of a whole compiler, or as reading every generated assembly code.
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- or as reading every generated assembly code.
What a Compiler Does with FP Code

1. **Parse** literal constants from the source code.
2. Perform some **optimizations**, e.g. constant propagation.
3. **Emulate** primitive operations missing from the target, e.g. integer ↔ float conversions.
4. **Output** constants to the assembly code.
How CompCert Handled FP Arithmetic Before

Earlier CompCert: *axiomatized* floating-point arithmetic.
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**Consequences**

- Parsing done through **external functions**, e.g. `strtod`.
  - “rounding error for values very close to half-way points”.

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- No proof of semantics preservation.
  - ⇒ **possibly incorrect** code transformations.
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1 Introduction

2 CompCert, a formally-verified compiler

3 Flocq, a Coq formalization of FP arithmetic
   - Floating-point formats
   - Operations and specification

4 CompCert with floating-point support

5 Conclusion
Flocq’s Binary FP Numbers

**Definition (Floating-point numbers as a sum type)**

```ocaml
Inductive binary_float :=
  | B754_zero : bool -> binary_float
  | B754_infinity : bool -> binary_float
  | B754_nan : binary_float
  | B754_finite : forall (s : bool) (m : positive) (e : Z), bounded m e = true -> binary_float.
```

- parametrized by precision and range of exponent,
- supports signed zeros, infinities, (sub)normal numbers,
- ignores NaN payload (and sign).
Floating-point Operators

Supported operations:

- addition, multiplication, division, square root,
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Critical feature: these are **computable** functions.
IEEE-754 Compliance

**Theorem (Bmult_correct)**

Given $x$ and $y$ two binary float numbers, $m$ a rounding mode, if $z = \text{round}(m, \text{B2R}(x) \times \text{B2R}(y))$, we have

\[
\begin{align*}
\text{B2R}(\text{Bmult}(m, x, y)) &= z & \text{if } |z| < 2^E, \\
\text{Bmult}(m, x, y) &= \text{overflow}(m, \text{Bsign}(x) \times \text{Bsign}(y)) & \text{otherwise}.
\end{align*}
\]
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   - Parsing and output of numeric literals
   - Constant propagation
   - Conversions from/to Integers

5. Conclusion
Parsing and Output of Numeric Literals

How to parse 0.314e1 in the C input code?

1. Parse integers 314 and 1.
2. Normalize into $314 \cdot 10^{-2}$.
3. Perform a FP division with Flocq: $\text{round}(\text{NE}, 314/100)$. 
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How to pass it to the assembler?

1. Ask Flocq for the bit-level representation.
2. Output it as an integer: `.quad 0x40091eb851eb851f`
Constant Propagation

Source code

```c
inline double f(double x) {
    if (x < 1.0) return 1.0; else return 1.0 / x;
}
double g(void) {
    return f(3.0);
}
```

Note: rounding to nearest was assumed.
**Constant Propagation**

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### After inlining and constant propagation

```c
double g(void) {
    return 0x1.5555555555555p-2;
}
```

Note: rounding to nearest was assumed.
Emulation: Conversion from/to Integers

Some conversions are not supported by target architectures,

- so we emulate them with some sequences of operations,
- and we have formally proved the semantics preservation.

Example (From unsigned to double)

\[
\text{x86-SSE2 converts to binary64 only from signed 32-bit integers.}
\]

\[
n < 0 \text{ x80000000 } \Rightarrow \text{(double)}((\text{int})(n - 0 \text{x80000000})) + 0x1. \text{p31}
\]

\[
\text{PowerPC does not support conversion from integers to binary64.}
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\text{fmake (0 x43000000, n \text{x80000000}) - fmake (0 x43000000, 0 x80000000)}
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5 Conclusion
   - Inconsistencies with the environment
   - Performances
   - Conclusion
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**Assumption:** the target environment is correctly formalized.
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**Broken assumptions**
- Nobody messed with the control flags of the processor.
Inconsistencies with the Environment

Assumption: the target environment is correctly formalized.

Broken assumptions

- Nobody messed with the control flags of the processor.
- NaNs have a single representation (no payload nor sign).
Performances: FFTW Pseudo-Benchmark

Example (Fastest Fourier Transform in the West)

```c
/* Generated by: ../../../genfft/gen_r2r.native -compact -variables 4 -pipeline-
   latency 4 -redft01 -n 8 -name e01_8 -include r2r.h */
void e01_8(const R *I, R *O, stride is, stride os, INT v, INT ivs, INT ovs)
{
    const E KP1_662939224 = ((E) +1.662939224605090474157576755235811513477121624);
    const E KP1_111140466 = ((E) +1.11114046603920449485661627897065748749874382);
    const E KP390180644 = ((E) +0.39018064403225635696569736954044481855383236);
    const E KP1_961570560 = ((E) +1.96157056080640898252364472268478073947867462);
    ...
    for (i = v; i > 0; i = i - 1, I = I + ivs, O = O + ovs) {
        E T7, Tl, T4, Tk, Td, To, Tg, Tn;
        {
            E T5, T6, T1, T3, T2;
            T5 = I[(is[2])];
            T6 = I[(is[6])];
            T7 = ((KP1_847759065) * (T5)) + (KP765366864 * T6));
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    T7 = (((KP1_847759065) * (T5)) + (KP76536864 * T6));
    T1 = ((KP76536864 * T5) - ((KP1_847759065) * (T6)));
    ...
```

Target: x86-32 with SSE2 arithmetic (everything fits in L1 cache).
Compilers: GCC 4.6.3 (-O3) vs CompCert 1.13.
Results: CompCert’s compiled code is 25% slower than GCC’s, but 160% faster than GCC’s at -O0.
Features

- simple yet useful semantics for FP numbers (IEEE-754!),
- no dependencies on the host system during compilation,
- a complete formal proof of semantics preservation
  (about 3000 new lines of Coq proofs).
## Conclusion

### Features
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- no dependencies on the host system during compilation,
- a complete formal proof of semantics preservation
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### Current limitations
- rounding to nearest is assumed,
- “float” computations are done in binary64,
- few optimizations (missing some range information),
- incorrect assumption about the binary representation of NaNs.
Questions?

CompCert:  http://compcert.inria.fr/
Flocq:    http://flocq.gforge.inria.fr/
Verasco:  http://verasco.imag.fr/