Verification of Floating-Point Software

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Abstract

Floating point computation presents a number of problems for formal verification. Should one treat the actual details of floating point operations, or accept them as imprecisely defined? or should one ignore round-off error altogether, and behave as if floating point operations are perfectly accurate? There is the further problem that a numerical algorithm usually only approximately computes some mathematical function, and we often do not know just how good the approximation is, even in the absence of round-off error.

ORA has developed a theory of asymptotic correctness which allows one to verify floating point software with a minimum entanglement in these problems. We describe this theory and its implementation in the Ariel C verification system, also developed at ORA. We illustrate the theory using a simple program which finds a zero of a given function by bisection.
Verification of Floating-Point Software

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Difficulties

- Machine real arithmetic does not have nice mathematical properties
- Doesn't match ideal arithmetic (overflow, round-off, underflow)
- Programs don't satisfy the specification we'd like them to
Asymptotic Correctness

• Specify "ideal behavior" of the program (e.g. "program computes the square root of its input")

• Verify that if program is run on a sequence of machines converging to perfect accuracy, then program's behavior converges to ideal behavior
Advantages of the Asymptotic Approach

- Machine real arithmetic can be specified loosely
- Specifications can be written in terms of ideal behavior
- Verification does not require roundoff error analysis
- Verifies logical correctness — absence of "bugs" from inaccuracy of machine arithmetic that are not related to error magnitude.
Nonstandard analysis

\[ \mathbb{R} \subseteq \mathbb{R}^* \]

Standard part map

\[ st : \mathbb{R}^* \rightarrow \mathbb{R} \]

rounds off a finite nonstandard real to an infinitely close standard real.

**Continuity**

\( f \) is continuous at \((a_1, \ldots, a_n)\) if

\[ st(f(a_1, \ldots, a_n)) = f(st(a_1), \ldots, st(a_n)) \]

**Differentiation by algebraic manipulation**

Let \( st(\epsilon) = 0, \epsilon \neq 0 \). For all standard \( x \),

\[
\frac{d(x^2)}{dx} = st\left( \frac{(x + \epsilon)^2 - x^2}{\epsilon} \right) \\
= st\left( \frac{2\epsilon x + \epsilon^2}{\epsilon} \right) \\
= st(2x + \epsilon) \\
= 2x
\]
Nonstandard Analysis

- Asymptotic approach can be formalized naturally in nonstandard analysis using infinitesimals

- Primitive operations are assumed to return values which are infinitely close to the ideal values when the arguments and ideal answers are finite

- Programs are specified to have behaviors infinitely close to ideal behavior when inputs are finite
Finding Roots of a Continuous Function

- `find_zero` searches for a root of a user-supplied function \( F \) by bisection.

- At each iteration, it tests to see if the values of \( F \) at the left endpoint and the midpoint are of opposite sign, and changes one of the endpoints to the midpoint so as to keep a root between the two endpoints.

- The program terminates when it finds a root or when it reaches a user-supplied bound on the number of iterations.
float find_zero(left0, right0, maxit) {
    float left0, right0;
    int maxit;
    {
        float left, right, center;
        float cval, lval0, rval0;
        int numit;

        numit = 0;

        lval0 = F(left0);
        rval0 = F(right0);

        left = left0;
        right = right0;
        center = (left + right)/2.0;
        cval = F(center);

        while(cval != 0.0 && numit < maxit) {
            if (lval0 * cval < 0)
                right = center;
            else
                left = center;
            center = (left + right)/2.0;
            cval = F(center);
            lval0 = F(left);
            numit = numit + 1;
        }

        return(center);
    }
}

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Specification of find_zero

IF F is continuous and find_zero is started up with

- left0 and right0 not "large";
- maxit "large";
- $F(left0)$ and $F(right0)$ of opposite sign

THEN find_zero terminates normally (i.e. without an exception) and the value output is "close to" some zero of F.
Attempted Verification

- Proof of termination is easy.

- Proof that termination is normal is a bit harder. Must prove that no overflow happens. To prove this, must prove that the values of the endpoints stay in some range of numbers which are not "large".
How would we prove that the program returns an approximation to a root?

- Prove when the program terminates, the endpoints are “close”. This follows from the fact that the program halves the interval a “large” number of times.

- Prove there’s always a root between the endpoints. This should follow from the way the program decides whether to move the left endpoint or the right. From this we’d get center “close to” a root.

Unfortunately, it’s not true that there’s always a root between the endpoints.
The Bug

• In the test statement, can have lval0 and cval of opposite sign, but have the product underflow to 0. This causes the program to move the wrong endpoint.

• Tests bear out this bug.
Possible Fixes

Several ways to fix this bug

• Change test to

\[(lval0 < 0 \&\& cval >= 0) ||
(lval0 >= 0 \&\& cval < 0)\]

• Change test so instead of always testing left endpoint against midpoint, it always tests the endpoint with the larger value of F against the midpoint.
This doesn’t necessarily keep a root between the endpoints, but it delivers an approximation to a root anyway.
Ariel

- Verification system for subset of C including real arithmetic and some UNIX system calls.
- Implements nonstandard formalization of the asymptotic approach.
Semantic Verification

- Ariel verifies programs by generating a description of the program's denotation in a higher-order language (the Clio metalanguage).
- Specifications are statements about the denotation in the Clio metalanguage.
- Verification is a proof of the specification directly from the description of the denotation in Clio theorem prover.
- Specifications can be any statement about the program's denotation which can be expressed in the Clio, including termination.
C Semantics

- A "run" of the program is modeled as a sequence of events

- Events are:
  - the event of going into a certain state
  - terminating and returning a value
  - terminating and returning no value
  - raising an exception
  - an "unknown" event

- The semantics of the program is expressed as a collection of axioms saying which sequences of events can happen in the course of executing the program.
Sample Verifications

- **ZBRENT** — a program which finds zeros of a continuous function by bisection

- **SWAP** — a very simple program to swap the contents of 2 locations which contains a surprising bug

- **HOSTILE BOOSTER** — a suite of programs, developed by Applied Technology Associates for SDIO, that estimate hostile booster trajectories. This verification is currently in progress.

- **SECURE DEVICE DRIVER** — specification and verification of security for an Ethernet device driver. Currently in progress.