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Accelerating Correctly Rounded Floating-Point Division when the Divisor Is Known in Advance

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Abstract—We present techniques for accelerating the floating-point computation of \(x/y\) when \(y\) is known before \(x\). The proposed algorithms are oriented toward architectures with available fused-mac operations. The goal is to get exactly the same result as with usual division with rounding to nearest. It is known that the advanced computation of \(1/y\) allows performing correctly rounded division in one multiplication plus two fused-macs. We show algorithms that reduce this latency to one multiplication and one fused-mac. This is achieved if a precision of at least \(n+1\) bits is available, where \(n\) is the number of mantissa bits in the target format, or if \(y\) satisfies some properties that can be easily checked at compile-time. This requires a double-word approximation of \(1/y\) (we also show how to get it). These techniques can be used by compilers to accelerate some numerical programs without loss of accuracy.

Index Terms—Computer arithmetic, floating-point arithmetic, division by software, division with fused-mac, compilation optimization.

1 MOTIVATION OF THIS RESEARCH

We wish to provide methods for accelerating floating-point (FP for short) divisions of the form \(x/y\) when \(y\) is known before \(x\), either at compile-time (i.e., \(y\) is a constant; in such a case, much precomputation can be performed) or at runtime. We want to get the result more quickly than by just performing a division, yet with the same accuracy: We need a correctly rounded result, as required by the IEEE 754 Standard for FP arithmetic [1], [6].

Divisions by constants are a clear application of our work. There are other applications, for instance, when many divisions by the same \(y\) are performed (an example is Gaussian elimination).

We assume that a fused multiply-accumulator is available and that division is done in software (this happens, for instance, on RS6000, PowerPC, or Itanium architectures). In this paper, we focus on rounding to nearest only. Presentation of conventional division methods can be found in [4], [9], [12].

2 INTRODUCTION

For computing \(x/y\) when \(y\) is known in advance, a naive approach consists of computing the reciprocal of \(y\) (with rounding to nearest) and then, once \(x\) is available, multiplying the obtained result by \(x\). It is well-known that such a “naive method” does not always produce a correctly rounded result. And yet, if the probability of getting an incorrect rounding was small enough, one could choose to use that method anyway, to check if the result is correctly rounded and to perform some correction step when this is not the case. Also, one could imagine that there might exist some values of \(y\) for which the naive method always work (for any \(x\)). For these reasons, we have decided to dedicate a short section to the analysis of the naive method.

Our main approach starts as previously: Once \(x\) is known, it is multiplied by the precomputed reciprocal of \(y\). Then, a “remainder” is computed and used to correct the final result. This does not require testing. That approach looks like the final steps of a Newton-Raphson division. It is clear from the literature that the iterative algorithms for division require an initial approximation of the reciprocal of the divisor and that the number of iterations is reduced by having a more accurate initial approximation. Of course, this initial approximation can be computed in advance if the divisor is known, but some care is needed to get correctly rounded results at low cost.

In Section 5.1, we show that, under some conditions on \(y\), that could be checked at compile-time, we can return a correctly rounded quotient using one multiplication and one fused-mac. In Section 5.2, we show that, if a larger internal precision than the target precision is available (one more bit suffices), then we can always return a correctly rounded quotient using one multiplication and one fused-mac.

To make this paper easier to read and to save space, we have put all proofs, tables, intermediate lemmas, and supplementary material in an appendix which can be found on the Computer Society Digital Library at http://computer.org/tc/archives.htm or on our own web site [2].

3 DEFINITIONS AND NOTATIONS

Define \(\mathbb{M}_n\) as the set of exponent-unbounded, \(n\)-bit mantissa, binary FP numbers (with \(n \geq 1\)), that is:

\[
\mathbb{M}_n = \{ M \times 2^E, 2^{n-1} \leq M \leq 2^n - 1, M, E \in \mathbb{Z} \} \cup \{0\}.
\]

It is an “ideal” system, with no overflows or underflows. We will show results in \(\mathbb{M}_n\). These results will remain true in actual systems that implement the IEEE-754 standard, provided that no overflows or underflows do occur. The mantissa of a nonzero element \(M \times 2^E\) of \(\mathbb{M}_n\) is the number \(m(x) = M/2^n - 1\).

We assume that the reader is familiar with the notions of rounding modes, ulps, floating-point successor, and predecessor. See [6] for definitions. In the following, \(o_d(t)\) means \(t\) rounded to the nearest even, \(o_d(t)\) means \(t\) rounded to \(-\infty\), and \(o_u(t)\) means \(t\) rounded to \(+\infty\).

4 PRELIMINARY RESULTS

4.1 The Naive Method

As said in the introduction, we have to evaluate \(x/y\) and \(y\) is known before \(x\), where \(x\) and \(y\) belong to \(\mathbb{M}_n\). An obvious solution consists of precomputing \(z = 1/y\) (or, more precisely, \(z\) rounded-to-nearest, that is, \(z_k = o_u(1/y)\)) and then multiplying \(x\) by \(z_k\). We will refer to this as “the naive method.” We assume round-to-nearest mode.

4.1.1 Maximum Error of the Naive Solution

Property 1. The naive solution returns a result that is at most at distance \(1.5\) ulps from the exact result if \(m(x) < m(y)\) (reminder: \(m(w)\) is the mantissa of \(w\)) and \(1\) ulp from the exact result if \(m(x) \geq m(y)\).

Property 1 gives tight bounds: There are values \(x\) and \(y\) for which the naive solution leads to an error very close to 1.5 ulps. More precisely,

Property 2. We have shown [2] that the maximum error of the naive algorithm can be obtained through a reasonably fast algorithm. This maximum error converges to 1.5 ulps as \(n \to \infty\).
For instance, in the IEEE-754 double precision format \( (n = 53) \), the division of \( x = 2^{63.435.44} \) by \( y = 9.067.199.120.521.205 \) by the naive algorithm leads to an error equal to \( 1.4999999739 \cdots \) ulps.

### 4.1.2 Probability of Getting a Correctly Rounded Result Using the Naive Solution

For the first few values of \( n \), we have computed, through exhaustive testing, the proportion of couples \((x, y)\) for which the naive method gives an incorrectly rounded result. The proportion seems to converge, as \( n \) grows, to a constant value that is around 27 percent. More precisely,

**Conjecture 1.** Assuming a uniform distribution of the mantissas of FP numbers, rounding to nearest, and \( n \) bits of mantissa, the probability that the naive method returns a result different from \( o_r(x/y) \) goes to \( 0.2708 \cdots \) as \( n \) goes to \( +\infty \).

This conjecture is a “half-conjecture” only since we have a rough sketch of a proof [2]. This tends to show that, for any \( n \), the naive method gives a proportion of incorrectly rounded results that is far too large to be neglected.

### 4.1.3 Values of \( y \) for which the Naive Method Always Works

Depending on \( n \), there are a very few values of \( y \) for which the naive method always works (i.e., for all values of \( x \)). For instance, for \( n = 13 \), the four values of \( y \) between 1 and 2 for which the naive method always works are 1, 4.411/4.096, 4.551/4.096, and 4.915/4.096. We are not able to compute them much faster than by exhaustive testing, which does not allow us to tackle the most interesting values of \( n \), namely, 24, 53, and 113.

### 4.2 Division with One Multiplication and Two Fused-Macs

On some modern processors (such as the PowerPC, the IBM RISCSystem/6000 [11], and IA64-based architectures [3], [10]), a fused-multiply accumulate instruction (fused-mac) is available. This makes it possible to evaluate an expression with one multiplication and two fused-macs, once Kahan [7] explains that the fused-mac allows us to compute remainders exactly. This is done as follows.

**Property 3.** Let \( x, y \in \mathbb{R} \) such that \( q \in \{ o_r(x/y), o_e(x/y) \} \). The remainder \( r = x - qy \) is computed exactly with a fused-mac. That is, \( o_e(x/y) = x - qy \).

We are going to examine require a double-word approximation to \( 1/y \), that is, two FP values \( z_k \) and \( z_l \) such that \( z_k = o_r(1/y) \) and \( z_l = o_e(1/y - z_k) \). The only reasonably fast algorithm we know for getting these values requires a fused-mac. Using Property 3, \( z_k \) and \( z_l \) can be computed as follows.

**Property 4.** Assume \( y \in \mathbb{R} \), \( y \neq 0 \). The following sequence of three operations computes \( z_k \) and \( z_l \) such that \( z_k = o_r(1/y) \) and \( z_l = o_e(1/y - z_k) \):

\[
\begin{align*}
z_k &= o_r(1/y), \\
\rho &= o_e(1 - yz_k), \\
z_l &= o_e(\rho/y).
\end{align*}
\]

### 5 Proposed Techniques

#### 5.1 Division with One Multiplication and One Fused-Mac

Using the method presented in Section 3.2, we could compute \( x/y \) using one multiplication and two fused-macs, once \( x \) is known. Let us show that, in many cases, one multiplication and one fused-mac (once \( x \) is known) do suffice. To do this, we need a double-word approximation to \( 1/y \). Let us first see how can such an approximation be computed.

#### 5.1.1 Preliminary Result: Getting a Double-Word Approximation to \( 1/y \)

Kahan [7] explains that the fused-mac allows us to compute remainders exactly. This is done as follows.

**Algorithm 3**

\[
\text{Algorithm 3} \text{ is the integer } (y \text{ is the mantissa of } y).\]

This algorithm almost always works for \( n \leq 7 \), it always works. Exhaustive searching [2] shows that, for \( n \leq 29 \), there are more than 98.7 percent of values of \( y \) for which the algorithm returns a correctly rounded quotient for all values of \( x \) (these figures have been obtained through exhaustive checking). Moreover, in the other cases (see the proof of Theorem 2 in [2]), for a given \( y \), there is at most one value of the mantissa of \( x \) (that can be computed in advance) for which the algorithm may return an incorrectly rounded quotient.

**Theorem 2.** Algorithm 2 gives a correct result (that is, \( q_2 = o_e(x/y) \)) as soon as at least one of the following conditions is satisfied:

1. The last mantissa bit of \( y \) is a zero;
2. \( |z_1| < 2^{-n-2-e} \), where \( e \) is the exponent of \( y \) (i.e., \( 2^e \leq |y| < 2^{e+1} \));
3. Algorithm 3, given below, returns true when the input value is the integer \( Y = x \times 2^{n-1-e} \), where \( e \) is the exponent of \( y \) (\( Y \) is the mantissa of \( y \), interpreted as an integer).

**Algorithm 3.** We give the algorithm as a Maple program (to make it more didactic). If it returns “true,” then Algorithm 2 always returns a correctly rounded result when dividing by \( y \). It requires the availability of \( 2n + 1 \)-bit integer arithmetic.

\[
\text{TestY}(Y, n) \text{ is the integer (y)}.
\]

local Pminus, Qminus, Xminus, OK, Pplus, Qplus, Xplus;

Pminus := (1/Y) mod 2^(n+1);

if (Qminus >= 2^(n-1)) and (Xminus >= 2^(n-1)) then OK := false; else OK := true;
Pplus := 2^(n+1) - Pminus; Qplus := (Pplus-1) / 2;
Xplus := (Pplus * Y + 1) / 2^(n+1);
if (Qplus >= 2^(n-1)) and (Xplus >= 2^(n-1))
then OK := false end if; end if;
print(OK)
end proc;

Translation of Algorithm 3 into a C or Fortran program is easily
done since computing a modular reciprocal modulo a power of
two requires a few operations only, using the extended Euclidean
GCD algorithm [8]. Algorithm 3 also computes the only possible
mantissa X for which, for the considered value of Y, Algorithm 2
might not work. Hence, if the algorithm returns false, it suffices to
check this very value of X to know if the algorithm will always work
or if it will work for all Xs but this one.

Let us discuss the consequences of Theorem 2.

• Condition “the last mantissa bit of y is a zero” is easily
checked on most systems. Hence, that condition can be
used for accelerating divisions when y is known at
runtime, soon enough before x. That condition allows us
to accelerate half divisions;

• Assuming a uniform distribution of z in
(-2^-n-1+e, +2^-n-1-e), which is reasonable (see [5]), Condition
“|z| < 2^-n-2-e” allows us to accelerate half of the
remaining cases;

• Our experimental testings up to n = 24 show that Condition
“Algorithm 3 returns true” allows us to accelerate
around 39 percent of the remaining cases (i.e., the cases for
which the last bit of y is a 1 and |z| ≥ 2^-n-2-e). If
Algorithm 3 returns false, then checking the only value of
x for which the division algorithm might not work suffices
to deal with all remaining cases. This requires much more
computation: It is probably not interesting if y is not
known at compile-time.

5.2 If a Larger Precision than Target Precision Is
Available

A larger precision than the target precision is frequently available.
A typical example is the double extended precision that is
available on Intel microprocessors. We now show that, if an
internal format is available, with at least n + 1-bit mantissas (which
is only one bit more than the target format), then an algorithm very
similar to Algorithm 2 always works. In the following, \( o_{n+1}(x) \)
means x rounded to n + p bits, with rounding mode t. Define
\( z = 1/y \). We assume that, from y, we have computed
\( z_0 = o_n(z) \) and
\( z_t = o_{n+1}(z - z_0) \). They can be computed through:

\[ z_0 = o_n(1/y), \quad p = o_n(1 - yz_0), \quad z_t = o_{n+1}(p/y). \]

We suggest the following 2-step method:

Algorithm 4 (Division with one multiplication and one fused-
mac). Compute:

\( q_1 = o_{n+1}(xz_t), \quad q_2 = o_n(xz_0 + q_1) \).

Theorem 3. Algorithm 4 always returns a correctly rounded quotient.

If the first operation returns a result with more than n + 1 bits,
the algorithm still works. We can, for instance, perform the first
operation in double extended precision if the target precision is
double precision.

6 COMPARISONS

Let us give an example of a division algorithm used on an
architecture with an available fused-mac. In [10], Markstein
suggests the following sequence of instructions for double-
precision division on IA-64. The intermediate calculations are
performed using the internal double-extended format. The first
instruction, \( \text{frcpa} \), returns a tabulated approximation to the
reciprocal of the operand, with at least 8.886 valid bits. When two
instructions are put on the same line, they can be performed “in
parallel.” The returned result is the correctly rounded quotient
with rounding mode \( \text{frcpa} \).

Algorithm 5 (Double precision division. This is Algorithm 8.10
of [10])

1. \( z_1 = \text{frcpa}(y) \);
2. \( e = o_n(1 - yz_1) \);
3. \( z_2 = o_n(z_1 + e) \);
4. \( e_1 = o_n(e \times e) \);
5. \( z_3 = o_n(z_2 + z_2e_1) \);
6. \( q_1 = o_n(xz_1) \);
7. \( r = o_n(x - yq_1) \);
8. \( q = o_n(q_1 + rz_2) \).

This algorithm requires eight FP latencies, and uses 10 instruc-
tions. The last three lines of this algorithm are Algorithm 1 of this
paper (with a slightly different context since Algorithm 5 uses
extended precision). Another algorithm also given by Markstein
(Algorithm 8.11 of [10]) requires seven FP latencies only, but uses
11 instructions. The algorithm suggested by Markstein for
extended precision is Algorithm 8.18 of [10]. It requires eight FP
latencies and uses 14 FP instructions.

These figures show that replacing conventional division \( x/y \)
by specific algorithms whenever y is a constant or division by the
same y is performed many times in a loop is worth being done. For
double-precision calculations, this replaces seven FP latencies by
three (using Algorithm 1) or two (using Algorithm 2 if y satisfies
the conditions of Theorem 2 or Algorithm 4 if a larger internal
precision—e.g., double-extended precision—is available). There-
fore, whenever an even slightly larger precision is available (one
more bit suffices), Algorithm 4 is of interest. Algorithm 2 is
certainly interesting when the last bit of y is a zero and, possibly,
when \( |z| < 2^{-n-2} \). In the other cases, the rather large amount of
computation required by checking whether the algorithm can be
used (we must run Algorithm 3 at compile-time) limits its use to
divisions by constants in applications for which compile time
can be large and running time must be as small as possible.

7 CONCLUSION

We have presented several ways of accelerating a division \( x/y \),
where y is known before x. Our methods could be used in
optimizing compilers, to make some numerical programs run
faster, without any loss of accuracy. Algorithm 1 always works and
does not require much precomputation (so it can be used even if y
is known a few tens of cycles only before x). Algorithm 2 is faster
and yet it requires much precomputation (for computing \( z_0 \) and \( z_t \)
and making sure that the algorithm works), so it is more suited for
division by a constant. Algorithm 4 always works and requires two
operations only once x is known, but it requires the availability of a
slightly larger precision.

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