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To cite this version:
Nicolas Fabiano, Jean-Michel Muller. Algorithms for triple-word arithmetic. 2018. hal-01869009

HAL Id: hal-01869009
https://hal.archives-ouvertes.fr/hal-01869009
Submitted on 6 Sep 2018

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Algorithms for triple-word arithmetic
Nicolas Fabiano and Jean-Michel Muller

Abstract—Triple-word arithmetic consists in representing high-precision numbers as the unevaluated sum of three floating-point numbers. We introduce and analyze various algorithms for manipulating triple-word numbers. Our new algorithms are faster than what one would obtain simply by using floating-point expansion algorithms in the particular case of expansions of length 3, for a comparable accuracy.

1 INTRODUCTION AND NOTATION

Numerical computations sometimes require a precision significantly higher than the one offered by the basic floating-point formats. This occurs for instance when evaluating transcendental functions with correct rounding: it is almost impossible to guarantee last-bit accuracy in the final result if all intermediate calculations are done in the target precision. For instance, the CRLibm library [3] of correctly rounded elementary functions uses “double-double” or “triple-double” [12], [13] operations in the last steps of the evaluation of approximating polynomials.

Double-word and Triple-word arithmetics consist in representing a real number as the unevaluated sum of two and three floating-point numbers, respectively. They are frequently called “double double” and “triple double”, because in practice the underlying format being used is the binary64/double precision format of the IEEE 754 Standard on Floating-Point Arithmetic [6], [17].

Double-word arithmetic had been useful for implementing BLAS [15]. Bailey, Barrio and Borwein [1] give several timely examples in mathematical physics and dynamics where higher precisions are needed.

A generalization of these arithmetics is the notion of floating-point expansion [21], [23], [9], where a high-precision number is represented as the sum of $n$ floating-point numbers.

Arbitrary precision libraries such as GNU-MPFR [5] have the advantage of being versatile, but may involve a significant penalty in terms of speed and memory consumption if one only requires computations accurate within around 150 bits in a few critical parts of a numerical program.

Algorithms for double word arithmetic have been presented in [14], [8]. The purpose of this paper is to introduce and analyze efficient algorithms for performing the arithmetic operations in triple word arithmetic. Our goal is to obtain algorithms that are faster to the ones we could obtain simply by using floating-point expansion algorithms in the particular case $n = 3$, for a comparable accuracy.

In the following, we assume a radix-2, precision-$p$ floating-point (FP) arithmetic system, with unlimited exponent range and correct rounding. As a consequence, our results will apply to “real-world” binary floating-point arithmetic, such as the one specified by the IEEE 754-2008 Standard provided that underflow and overflow do not occur. We also assume the availability of an FMA (fused multiply-add) instruction. Such an instruction evaluates expressions of the form $ab + c$ with one final rounding only.

The notation $a | b$ means “$a$ divides $b$”. The notation $\text{RN}(t)$ stands for $t$ rounded to the nearest FP number, ties-to-even, and $\text{RU}(t)$ (resp. $\text{RD}(t)$) stands for $t$ rounded towards $+\infty$ (resp. $-\infty$). If $x \neq 0$ is a real number, then we define three functions $\text{ulp}(x)$, $\text{ulp}(x)$, and $\text{uls}(x)$ as follows:

- $\text{ulp}(x) = 2^\lfloor \log_2 |x| \rfloor$;
- $\text{ulp}(x) = \text{ulp}(x) \cdot 2^{-p+1}$;
- $\text{uls}(x)$ is the largest power of 2 that divides $x$.

When $x$ is a FP number, $\text{ulp}(x)$ is the weight of its most significant bit, $\text{ulp}(x)$ is the weight of its least significant bit, and $\text{uls}(x)$ is the weight of its rightmost nonzero bit.

The number $u = 2^{-p} = \frac{1}{2} \text{ulp}(1)$ denotes the roundoff error unit. When an arithmetic operation $a \nu b$ is performed, where $a$ and $b$ are FP numbers, what is effectively computed is $\text{RN}(a \nu b)$, and if $t$ is a real number and $T = \text{RN}(t)$, then

$$|t - T| \leq \frac{u}{1 + u} \cdot |t| \leq u \cdot |t| \text{ and } |t - T| \leq u \cdot |T|,$$

and more precisely

$$|t - T| \leq \frac{1}{2} \text{ulp}(t) \leq \frac{1}{2} \text{ulp}(T).$$

The algorithms presented in this paper (as well as the usual algorithms that manipulate double words or general expansions) use as basic blocks Algorithms 1, 2, and 3 below.
Algorithm 1 – Fast2Sum\((a, b)\). (3 operations) [4].

Require: \(\exists\) integers \(k_a \geq k_b, M_a, M_b\) (with \(|M_a|, |M_b| \leq 2^{p_1} - 1\), s.t. \(a = M_a \cdot 2^{k_a}\) and \(b = M_b \cdot 2^{k_b}\).

Ensure: \((s, e) = a + b \quad s \leftarrow \text{RN}(a + b) \quad z \leftarrow \text{RN}(s - a) \quad e \leftarrow \text{RN}(b - z)\)

Algorithm 2 – 2Sum\((a, b)\). (6 operations) [16], [11].

Ensure: \((s, e) = a + b \quad s \leftarrow \text{RN}(a + b) \quad a' \leftarrow \text{RN}(s - b) \quad b' \leftarrow \text{RN}(s - a') \quad \delta_a \leftarrow \text{RN}(a - a') \quad \delta_b \leftarrow \text{RN}(b - b') \quad e \leftarrow \text{RN}(\delta_a + \delta_b)\)

If there exist integers \(k_a \geq k_b, M_a, M_b\) (with \(|M_a|, |M_b| \leq 2^{p_1} - 1\), s.t. \(a = M_a \cdot 2^{k_a}\) and \(b = M_b \cdot 2^{k_b}\) (which holds if \(|a| \geq |b|\)) then values \(s\) and \(e\) computed by Algorithm 1 satisfy \(s + e = a + b\). Hence, \(e\) is the error of the FP addition \(s \leftarrow \text{RN}(a + b)\).

Algorithm 3 – 2Prod\((a, b)\). (2 operations) [10], [18], [17]

Ensure: \((\pi, e) = a \cdot b \quad \pi \leftarrow \text{RN}(a \cdot b) \quad e \leftarrow \text{RN}(a \cdot b - \pi)\) (FMA)

The values \(\pi\) and \(e\) computed by Algorithm 3 satisfy \(\pi + e = ab\). Algorithm 3 uses an FMA instruction (for computing \(\text{RN}(a \cdot b - \pi)\)).

Sometimes, we know in advance the value of \(s\) of \(\pi\). In that case, \(e\) can be computed saving the first operation, with algorithms denoted by for instance 2Sum\(_{2}\)\((s)(x, y)\).

When one defines a number as the unevaluated sum of two, three or more FP numbers, one has to explain to which extent they can “overlap”: after all the sum of the three double-precision/binary64 numbers 1, 2, and 4 is just a three-bit number, expressing it as the sum of three FP numbers does not make it more precise. Several definitions appear in the literature. The first needed in this paper is Priest’s definition:

Definition 1. The sequence \((x_i)\) is P-nonoverlapping (with Priest’s definition [22]) when \(\forall i, |x_{i+1}| < \text{ulp}(x_i)\).

We also introduce the following definition, more restrictive than Shewchuk’s definition [23]:

Definition 2. The sequence \((x_i)\) is F-nonoverlapping (with Fabiano’s definition) when \(\forall i, |x_{i+1}| \leq \frac{1}{2}\text{uls}(x_i)\).

The rest of the paper is organized as follows. Section 2 presents some other basic blocks that will be used in the rest of the paper, and some original results related to them. Section 3 proves that the classical algorithm to turn a arbitrary sequence into an expansion works for TW. Section 4 presents an algorithm to correctly round a TW, and proves it correctness. Section 5 does the same as section 3 for the sum of two TW. Section 6 presents two versions of an original algorithm for the product of two TW, and proves their correctness and tight error bounds. Sections 7 to 10 provide a similar analysis, in the case of the product of a DW by a TW, the reciprocal of a TW, the quotient of two TW, and the square root of a TW, respectively. Section 11 compares our results to the ones known for general \(n\)-word expansions, with \(n = 3\).

2 Other basic blocks

The Algorithms on TW presented in this paper use as basic blocks the 2Sum, Fast2Sum and 2Prod algorithms presented in the previous section, as well as the following, less classical, VecSum and VecSumErrBranch algorithms. Properties of these algorithms have been proven elsewhere [21], [19], [2], but in this paper, we will need specific properties, proven below.

2.1 VecSum

The VecSum algorithm first appears as a part of Priest’s normalization algorithm [21]. The name “VecSum” was coined by Ogita et al. [19]. The aim of this algorithm is to turn a sequence that is “slightly” nonoverlapping into one that is “more” nonoverlapping, with no error.

Algorithm 4 – VecSum\((x_0, \ldots, x_{n-1})\). (6n – 6 operations)

Ensure: \(e_0 + \cdots + e_{n-1} = x_0 + \cdots + x_{n-1}\)

\[ s_{n-1} \leftarrow x_{n-1} \]

for \(i = n - 2\) to 0 do

\[ s_i, e_{i+1} \leftarrow \text{2Sum}(x_i, s_{i+1}) \]

end for

\[ e_0 \leftarrow s_0 \]
There are several theorems related to this algorithm, that use different definitions of nonoverlapping. In what follows, we will use the following original result:

**Theorem 1.** Assume, after removing possible interleaving zeros, that we can write in a non-necessarily canonical way $x_i = M_i 2^{k_i - p_i + 1}$, $|M_i| < 2^p$, such that $\forall i \leq n - 2$, $k_{i-1} \geq k_{i+1}$, and $k_{n-2} \geq k_{n-1}$. Then VecSum($x_0, \ldots, x_{n-1}$) is $F$-nonoverlapping wIZ with the same sum.

In this case, Fast2Sum can be used instead of 2Sum, so that VecSum only costs $3n - 3$ operations.

**Proof:** Interleaving zeros in the input simply give some interleaving zeros in the output without changing the non-zero terms, so that we can suppose that we have removed them.

- Firstly, $\forall i, |s_i| \leq (2 - 2u)2^{k_i-1}$.
- Indeed, if by induction $|s_{i+1}| \leq (2 - 2u)2^{k_i}$, given $|x_i| \leq (2 - 2u)2^{k_i}$, we get $|s_{i+1}| + |x_i| \leq (4 - 4u)2^{k_i} \leq (2 - 2u)2^{k_i-1}$ so $|s_i| \leq (2 - 2u)2^{k_i-1}$.
- This gives $|e_i| \leq 2u2^{k_i-1}$, and justifies Fast2Sum being used.

We suppose that $|e_i| > \frac{1}{2}\text{ulp}(e_{i'})$ with $i' < i$. We also suppose WLOG that uls($e_{i'}$) = $u$. We easily get by induction that for all $i$, if $2^k |s_i, x_{i-1}, \ldots, x_0$, then $2^k |e_{i}, \ldots, e_0$. Yet $|e_i| \leq \frac{1}{2}\text{ulp}(s_{i-1})$ so $s_{i-1} \geq 1$ so $s_{i-1}$ is a multiple of $2u$. Given we want a $e_{i'}$ non-multiple of $2u$, that must be the case for one of the $x_j, j \leq i - 2$. In particular, we have $2^k \leq \frac{1}{2}$ so by isometry $2^k x_{i-2} \leq \frac{1}{2}$ so $2^{k_{i-1}} \leq \frac{1}{2}$, which contradicts $|e_i| \leq 2u2^{k_{i-1}}$.

The conditions on the input of this theorem are complex, so we will use the following corollary:

**Corollary 2.** Assume that we have $I \subset [1, n - 2]$ with no 2 consecutive indices such that

$$
\forall i \in [0, n - 2], i \notin I, \upf(x_{i+1}) = \frac{1}{2}\upf(x_i)
$$

$$
\forall i \in I, \upf(x_{i+1}) \leq 2^{n-2}\upa(x_i) \land \upf(x_{i+1}) \leq \frac{1}{4}\upf(x_{i-1})
$$

Then VecSum($x_0, \ldots, x_{n-1}$) is $F$-nonoverlapping with the same sum. In this case, Fast2Sum can be used, so that it only costs $3n - 3$ operations.

**Proof:** For $i \notin I$, we take $k_i = e_{x_i} - x_i$ the canonical exponent, and for $i \in I$, we take $k_i = \max(k_{i+1}, 1, e_{x_i})$. This is possible because: $2^{k_i+1-p_i+2}|x_i$ and $2^e_{x_i} - p_i+1|x_i$, which imply $2^k|x_i|$, and $|x_i| \leq 2^{e_{x_i}}$, which imply $|x_i| \leq 2 \cdot 2^{k_i}$.

For $i, i + 1 \notin I$, we have $k_{i+1} \leq k_i - 1$. For $i \in I$, we have on one hand $k_{i+1} \leq k_i - 1$ and $k_{i+1} \leq k_{i-1} - 2$ so $k_i \leq k_{i-1} - 1$.

### 2.2 VecSumErrBranch

Algorithm 5 below is similar to the previous one, but sums are computed starting from the larger terms, and some branching helps avoiding to return too many zero terms

**Algorithm 5 - VSEB($e_0, \ldots, e_{n-1}$). (6n - 6 operations & $n - 2$ tests)**

| Ensure | $y_0 + \cdots + y_{n-1} = e_0 + \cdots + e_{n-1}$ |
|        | $j \leftarrow 0$ |
|        | $e_0 \leftarrow e_0$ |
| for $i = 0$ to $n - 3$ do |
|        | $r_i, e_{i+1} \leftarrow 2\text{Sum}(e_i + e_{i+1})$ |
|        | if $e_{i+1} \neq 0$ then |
|        | $y_j \leftarrow r_i$ |
|        | incr $j$ |
|        | else |
|        | $e_{i+1} \leftarrow r_i$ |
| end if |
| end for |

We prove the following property, of Algorithm 5, that will be useful later on.

**Theorem 3.** If $(e_i)$ is $F$-nonoverlapping wIZ, then VSEB($x_0, \ldots, x_{n-1}$) is $P$-nonoverlapping with the same sum, provided that $p \geq n - 1$. In this case, Fast2Sum can be used, so that it only costs $3n - 3$ operations.

**Proof:** Again, interleaving zeros in the input can be ignored without changing anything, so we suppose that we have removed them. We write $e_i = M_i \cdot 2^{k_i}$ with $|M_i| < 2^p$ odd so that $|e_{i+1}| \leq \frac{1}{2}2^{k_i}$. By an easy induction, for all $i$, $r_{i-1}$ and $e_i$ are multiples of $2^{k_i}$.

* Let $i_0$ be such that $|e_{i_0}| = 2^{k_{i_0}}$. Let us show by induction that for all $i_0 \leq i \leq n - 2$, we have $|e_i| \leq 2^{k_{i_0}}(2 - 2^{2i-1})$.

- We can initialize with $i = i_0 - 1$, because what is transmitted to next step (playing the role of $r_{i_0-1}$) is $e_{i_0}$, which exactly satisfies the condition.

- We suppose that $|r_{i-1}| \leq 2^{k_{i_0}}(2 - 2^{2i-1})$.

We have $|e_{i+1}| \leq \frac{1}{2}2^{k_i} \leq \frac{1}{2}2^{k_{i-1}} \leq \cdots \leq 2^{i_0-i-1}2^{k_{i_0}}$.

Thus $|r_{i-1}| + |e_{i+1}| \leq 2^{k_{i_0}}(2 - 2^{2i-1})$, and this is a FP number because $i_0 \geq 1$ and $i \leq n - 2$ give $i_0 - i - 1 \geq -n + 2 \geq -p + 1$, so that $|r_i| \leq 2^{k_{i_0}}(2 - 2^{2i-1})$. This gives the result by induction.

In particular, with $j$ such that $y_j = r_{i_0-1}$, we have ulp($y_j$) ≥ $\frac{1}{2}|e_{i_0}| = 2 \cdot 2^{k_{i_0}}$ so $|y_{j+1}| < \text{ulp}(y_j)$.
When Fast2Sum can be used everywhere, we get a total

\[ \text{Theorem 4. If the total output would be P-nonoverlapping,} \]

\[ \text{provided that} \] \[ |e_{i_0}| > 2^{k_{i_0}}, \text{we similarly get that for all} \]

\[ i \geq i_0 \text{ such that} e_{i+1}, \ldots, e_i = 0, \text{we have} |r_i| \leq |e_{i_0}| + 2^{k_{i_0}}. \]

Indeed, the same proof replacing \( 2^{k_{i_0}}(2 \cdots) \) by \( |e_{i_0}| + 2^{k_{i_0}}(1 \cdots) \) works, except that the equality case can be reached in case of errors. In this case, this is sufficient given \( \text{ulp}(y_j) \geq 2|e_{i_0}| > |e_{i_0}| + 2^{k_{i_0}} \geq y_{j+1}. \]

Finally, we can use Fast2Sum. Indeed, we have \( 2^{k_{i}}|e_0, \ldots, e_i| \leq 2^{k_{i}} \cdot |e_i|_n \text{ and } |e_{i+1}| = 2^{k_{i}}. \]

Usually, we do not want to keep the complete output, but only a fixed number of terms. The resulting algorithm is denoted by \( \text{VSEB}(k)(e_0, \ldots, e_{n-1}). \)

It costs as many operations, but the number of tests depends on how this is performed in practice. In what follows, we will assume in our complexity analysis that everything is unrolled (which is reasonable because typically \( n = 4 \)), so that only the \( n - 2 \) tests are required.

**Theorem 4. If the total output would be P-nonoverlapping, then the relative error caused by keeping only the first \( k \) terms is bounded by \( 2^{k} - 4.2 \cdot 2^{k+1} \), provided that \( p \geq 6. \)

**Proof:** We have by P-nonoverlapping:

\[ \text{ufp}(y_k) \leq u \text{ufp}(y_{k-1}) \leq \cdots \leq u^k \text{ufp}(y_0) \]

\[ |y_k| + \cdots + |y_{n-1}| \leq (2 - 2u)(u^k + u^{k+1} + \cdots + u^n) \text{ufp}(y_0) \]

\[ |y_k + \cdots + y_{n-1}| \leq 2^k \text{ufp}(y_0) \]

\[ |y_0 + \cdots + y_{n-1}| \geq |y_0| - |y_1 + \cdots + y_{n-1}| \geq (1 - 2u) \text{ufp}(y_0) \]

\[ |y_k + \cdots + y_{n-1}| \leq \frac{2^k}{1 - 2u} |y_0 + \cdots + y_{n-1}| \]

Thus the relative error is bounded by \( 2^k + 4.2 \cdot 2^{k+1} \), provided that \( p \geq 5. \)

\[ \square \]

### 2.3 Composed algorithm

Algorithms VecSum and VSEB were designed to be composed. In that case, we note that the first 2Sum in VSEB can be skipped because \((e_0, e_1)\) is already a DW. When Fast2Sum can be used everywhere, we get a total of \( 6n - 9 \) operations and \( n - 2 \) tests.

## 3 Arbitrary Three FP Numbers to TW

Before manipulating Triple-Word numbers, we want to be able to turn any unevaluated sum of three FP numbers into a TW, with no error (this is the equivalent of the 2Sum algorithm for 3 FP numbers). We can use Algorithm 6, which can be found in [20, page 87] for general expansions:

**Algorithm 6 – ToTW \((a, b, c)\).** (21 operations & 1 test)

**Ensure:** \( \bar{r} \) TW and \( \bar{r} = a + b + c \)

\[ a_d, a_1 \leftarrow 2\text{Sum}(a, b) \]

\[ e_0, e_1, e_2 \leftarrow \text{VecSum}(d_0, d_1, c) \]

\[ r_0, r_1, r_2 \leftarrow \text{VSEB}(e_0, e_1, e_2) \]

We have,

**Theorem 5. If \( a, b, c \) are FP numbers, then toTW \((a, b, c)\) is a TW, provided that \( p \geq 4. \)

**Proof:** If \((e_0, e_1, e_2)\) is F-nonoverlapping, then Theorem 3 concludes.

First, \(|e_1| \leq \frac{1}{2} \text{ulp}(e_0)\) gives \((e_0, e_1)\) F-nonoverlapping. We denote \( s := \text{RN}(d_1 + 2) \) the intermediate value in \( \text{VecSum}(d_0, d_1, c). \)

- If \( e_1 \neq 0 \), we suppose WLOG that \( \text{uls}(e_1) = u \), and \( e_2 > \frac{3}{2}u \). Then \(|e_2| \leq \frac{1}{2} \text{ulp}(s)\) gives \( s \geq 1 \) so \( 2u |s| \) but \( e_1 \) is not divisible by \( 2u \) so \( d_0 \neq 0 \), hence \( |d_1| \leq \frac{1}{2} \text{ulp}(d_0) \leq \frac{3}{4}u. \)

Furthermore, \(|c + d_1| \geq 1 + \frac{1}{2}u \). Thus \(|c| \geq (1 + \frac{1}{2}u) - \frac{1}{2}u = 1\) so \( \text{ulp}(c) \geq 2u > 2|d_1| \) so \( s = c \) and \( e_2 = d_1 \), which is impossible since \(|e_2| > \frac{1}{2}u \geq |d_1| \).

So \((e_1, e_2)\) is F-nonoverlapping too.

- If \( e_1 = 0 \), then the same reasoning works with \( e_0 \) instead of \( e_1 \).

\[ \square \]

Another typical way of forming a TW consists in using any of the following algorithms, but with inputs that are DW instead of TW (with an implicit third term equal to zero, and simplifications obtained by removing useless operations).

## 4 Rounding of TW to FP Number

Once our calculations are done, we may want to obtain the FP number closest to our TW result. This is for instance the case when we are using TW numbers in intermediate calculations for implementing correctly rounded elementary functions. This can be done using Algorithm 7.

**Algorithm 7 – RoundTW \((x_0, x_1, x_2)\).** (3 operations & 4 tests)

**Require:** \( x \) TW

**Ensure:** \( y = \text{RN}(x) \)

\[ \text{if } \text{RN}(x_0 + 2x_1) \text{ inexact operation or } (\star) \text{RN}(-\left(\frac{1}{2}u - 2u^2\right) \cdot x_0) \neq x_1 \text{ then} \]

\[ y \leftarrow \text{RN}(x_0 + x_1) \]

\[ \text{else if } x_2 > 0 \text{ then} \]

\[ y \leftarrow \text{RU}(x_0 + x_1) \]

\[ \text{else if } x_2 < 0 \text{ then} \]

\[ y \leftarrow \text{RD}(x_0 + x_1) \]

\[ \text{else} \]

\[ y \leftarrow \text{RN}(x_0 + x_1) \]

\[ \text{end if} \]
Remark 1. Depending on the underlying architecture, the fact that the operation $x_0 + 2x_1$ is exact can be detected by checking a flag, but if this is too expensive to do, we can instead start computing Fast2Sum($x_0, 2x_1$) and test whether $z = y$ to know if $e$ is zero. This costs 2 more operations.

Remark 2. Instead of testing $x_2 > 0$ (resp. $x_2 < 0$), it may be better to test something like $x_2 > 64u|x_1|$ (resp. $x_2 < -64u|x_1|$) and to raise a warning if none of them is true, because it means that we are in the "grey zone" of rounding errors.

Theorem 6. If $\bar{x}$ is a TW, then FromTW($\bar{x}$) = RN($\bar{x}$), provided that $p \geq 4$.

Proof: First, if $x_0 + x_1$ is a FP number, then $y = x_0 + x_1$ anyway, and it is easy to check that $x_0 + x_1 = RN(\bar{x})$. We suppose for the rest of the proof that this is not the case.

Given $|x_1| < ulp(x_0)$, the first condition is false iff $x_0 + x_1$ is halfway between two adjacent FP numbers, or in a special case that can WLOG be reduced to $x_0 = 1 + 2u$ and $x_1 = \frac{3}{2}u$. When that first condition is false, the condition (1) is designed to be true in the special case, but false elsewise (because of the magnitude of $|x_1|$).

- If $x_0 + x_1$ is halfway between two adjacent FP numbers, then the rounding is decided by the sign of $x_2$.
- Otherwise, one easily checks that RN($x_0 + x_1$) = RN($x_0 + x_1$), given $|x_2| < ulp(x_1)$.

Remark 3. When we implement correctly rounded elementary functions, we may know that when TW are needed, this is because the final value $z$ is close to the midpoint of two adjacent FP numbers, so that Condition (1) can be skipped. This saves 1 operation and 1 test.

5 SUM

To compute the sum of two TW, we simply use the composition of VecSum and VSEB after a preliminary sort of the input. This gives Algorithm 8 below. That algorithm would of course also work to compute the sum of a DW and a TW, or of two DW, with same correctness theorem and same error bound but with less operations and tests.

Algorithm 8 – 3Sum($x_0, x_1, x_2, y_0, y_1, y_2$). (42 operations & 8 tests)

Require: $\bar{x}$ and $\bar{y}$ TW
Ensure: $\bar{r}$ TW and $\left|\frac{r - (\bar{x} + \bar{y})}{x+y}\right| \leq 2u^3 + 4.2u^4$

$z_{00}, z_{01}, z_{02} \leftarrow Merger((x_0, x_1, x_2), (y_0, y_1, y_2))$
$e_0, e_1, e_2 \leftarrow VecSum(z_{00}, z_{01}, z_{02})$
$r_0, r_1, r_2 \leftarrow VSEB(3)(e_0, e_1, e_2)$

5.1 Correctness of Algorithm 8

We have,

Theorem 7. Let $x_0, \ldots, x_5$ be FP numbers such that $\forall i, |x_{i+1}| \leq |x_i|$ and $\forall i, |x_{i+2}| < ulp(x_i)$.

Then VSEB(VecSum($x_0, \ldots, x_5$)) is P-nonoverlapping, provided that $p \geq 4$.

Remark 4. This theorem may not hold for more than 6 floating-point inputs. Indeed, for 7 inputs, we can consider $x_i = 1 - u, -1 + 2u, -u + u^2, u - u^2, u^2 - u^3, u^3 - u^4$ which gives $(e_i) = u, u^2, u^2, -u^3, -u^4, and finally (y_i) = u, 2u^2, -u^3, -u^4$ with $2u^2 = ulp(u)$.

This is why it is reasonable to use the notion of P-nonoverlapping for TW only, but not for general expansions, for which Algorithm 8 preserves ulp-nonoverlapping only [20, page 90].

Sketch of the proof: For space constraints, the proof is not detailed. The main steps are:

- prove by induction that $|s_i| < 2ulp(x_{i-1})$ and $|s_i| < 4ulp(x_i)$;
- if $e_i > \frac{1}{2}uls(e_j)$ for some $j < i$, deduce some conditions on $i$ and the nearby terms in various cases;
- conclude with a case study: $i \leq 3$ and $e_i > \frac{1}{2}uls(e_j)$; $i \geq 4$ and $e_i > \frac{1}{2}uls(e_j)$; or $0 < e_i < \frac{1}{2}uls(e_j)$.

5.2 Number of operations

In the Merge, if the last two numbers to sort are $x_2$ and $y_2$, there is no need to do it because they play symmetrical roles in 2Sum. Thus this part costs only 4 tests. In VecSum, there are for each block examples where Fast2Sum cannot be used, so it costs 30 operations. One easily checks that Fast2Sum can be used in VSEB, so it costs 12 operations and 4 tests.

6 PRODUCT OF TWO TW

To compute the product of two TW, we simply distribute the sub-products and aggregate the terms ensuring P-nonoverlapping, with an error as small as possible. The algorithms presented below guarantee commutativity, even if it is rarely useful in practice.

Algorithm 9 – 3Prod$^{+/−}(x_0, x_1, x_2, y_0, y_1, y_2)$. (46 operations & 2 tests)

Require: $\bar{x}$ and $\bar{y}$ TW; $p \geq 6$
Ensure: $\bar{r}$ TW and $\left|\frac{r - xy}{xy}\right| \leq 28u^3 + 107u^4$

$z_{00}^{+}, z_{00}^{-} \leftarrow 2Prod(x_0, y_0)$
$z_{01}^{+}, z_{01}^{-} \leftarrow 2Prod(x_0, y_1)$
$z_{10}^{+}, z_{10}^{-} \leftarrow 2Prod(x_1, y_0)$
$b_0, b_1, b_2 \leftarrow VecSum(z_{00}^{+}, z_{01}^{+}, z_{10}^{+})$
$c \leftarrow RN(b_2 + x_1y_1)$ (FMA)
$z_{31} \leftarrow RN(z_{10}^{+} + x_0y_2)$ (FMA)
$z_{32} \leftarrow RN(z_{01}^{+} + x_2y_0)$ (FMA)
$z_3 \leftarrow RN(z_{31} + z_{32})$
$e_0, e_1, e_2, e_3, e_4 \leftarrow VecSum(z_{00}^{+}, b_0, b_1, c, z_3)$
$r_0 \leftarrow e_0$
$r_1, r_2 \leftarrow VSEB(2)(e_1, e_2, e_3, e_4)$
6.1 Estimates of the different terms
We suppose WLOG that \(1 \leq x_0, y_0 < 2\), so that \(|x_1|, |y_1| < 2u\) and \(|x_2|, |y_2| < 2u^2\). Then, we have:
\[
1 \leq |z_{00}^+| < 4 \\
|z_{00}^-| \leq 2u : uls(z_{00}^0) \geq 4u^2 \\
|z_{00}^+|, |z_{00}^-| < 4u \\
|x_1|, |y_1| < 4u^2 - 4u^3 \\
|z_{3,1}, z_{3,2}| \leq 6u^2 \\
|s_3| \leq 20u^2
\]

6.2 Correctness of Algorithm 9
We have,

**Theorem 8.** If \(\bar{x}, \bar{y}\) are TW, then 3Prod_{3,3}^{CF}(x, y) is a TW, provided that \(p \geq 6\).

**Lemma 9.** For all FP numbers \(x, y, z = \frac{1}{2}\ulp(x)RN(x + y)\).

Proof of the lemma: If \(\ulp(y) \geq \frac{1}{2}\ulp(x)\), then \(\frac{1}{2}\ulp(x)|x + y|RN(x + y)\).

If \(\ulp(y) \leq \frac{1}{2}\ulp(x)\), then \(|y| < \frac{1}{2}|x|\) so \(|x + y| \geq \frac{1}{2}\ulp(x)\).

**Proof of the theorem:**
* First, let us prove that the last 2 lines are equivalent to computing \(r_0, r_1, r_2 = VSEB(3)(e_0, e_1, e_2, e_3, e_4)\).
  * If \(e_1 \neq 0\), then the fact that \(e_0 = RN(e_0 + e_1)\) concludes immediately.
  * If \(e_1 = 0\), one easily checks that \(|s_1|, |s_2|, |s_3| < 16u \leq \frac{1}{2}\ulp(z_0^+)|z_0^+|\) so that the next nonzero \(\epsilon_1\) is strictly less than \(\frac{1}{2}\ulp(e_0)\), which concludes.

* Then, let us prove that, with this equivalent version, \((r_0, r_1, r_2)\) is P-nonoverlapping.

We define \(\nu := RN(z_0^+ + z_{10}^+)|RN(x + y)|RN(x + y)\).

We want to show that \(\nu = RN(z_0^+ + z_{10}^+)|RN(x + y)|RN(x + y)\).

Thanks to Theorem 3, this would give \((r_0, r_1, r_2)\) P-nonoverlapping.

First, let us show that \((z_{00}, b_0, b_1, s_3)\) satisfies the conditions of Theorem 2.

Next, we always have \(\ulp(z_{00}) \geq 1\) much larger than four times any other number computed, and in case on they are non-zero \(\ulp(b_i) \leq \frac{1}{2}\ulp(b_i) < \frac{1}{2}\ulp(b_i)\).

For the rest of the sequence, we suppose WLOG that \(|x_1| \geq |y_1|\).

On one hand, we easily obtain \(|s_3| \leq 10\ulp(x_1)\).

On the other hand, Lemma 8 gives \(\ulp(z_0^+)|\alpha|\) with \(\frac{1}{2}\ulp(x_1) \leq u^2 < uls(z_{00})\) so \(\ulp(x_1)\).

- Case \(s_3 = 0\): we use \(I = \emptyset\). (nothing more to show)
- Case \(s_3 \neq 0\) and \(b_0 = 0\) (so \(b_1 = 0\)): we use \(I = \emptyset\) (iden)
- Case \(s_3 \neq 0\), \(b_0 \neq 0\) and \(b_1 = 0\): we use \(I = \{1\}\).

Indeed, we have \(\ulp(s_0) \leq \frac{1}{2}\ulp(z_{00}^+), \ulp(s_0) \leq 2u^2 \ulp(b_0)\), (using \(p \geq 6\))

- Case \(s_3 \neq 0\), \(b_0 \neq 0\) and \(b_1 \neq 0\): we use \(I = \{2\}\)

Indeed, we have \(\ulp(s_3) \leq 16\ulp(b_1) \leq \frac{1}{2}\ulp(b_0)\) and \(\ulp(s_0) \leq 2u^2 \ulp(b_1)\), (using \(p \geq 6\))

It also allows us to call Fast2Sum instead of the three 2Sum in this part of the algorithm.

- Then, let us show that \(e_4\) is F-nonoverlapping with the other \(e_i\).

Firstly, \(\ulp(s_3) \geq 2|e_4|\). Secondly, we have seen that \(\ulp(b_0), uls(b_1) \geq \frac{1}{2}\ulp(x_1) \geq 20|s_3| \geq ulp(s_3)\). (using \(p \geq 6\))

Thirdly, \(\ulp(s_{00}) \geq 2u > ulp(s_3)\).

Thus \(e_0, e_1, e_2\) are divisible by \(ulp(s_3) \geq 2|e_4|\).

6.3 Number of operations
Before the last 3 lines, we count 22 operations. There are 3 Fast2Sum in VecSum in the second line of the theorem, so that it costs 15 operations. Finally, the call to VSEB costs 9 operations and 2 tests. Thus the total is 46 operations and 2 tests.

**Remark 5.** The optimization that directly uses \(e_0 = r_0\) does not save any operation, but it saves the first branching, which is very interesting.

6.4 Bound on the error
**Theorem 10.** If \(\bar{x}, \bar{y}\) are TW, then the relative error committed by 3Prod_{3,3}^{CF}(x, y) is bounded by \(28u^3 + 107u^4\), provided that \(p \geq 6\).

Proof: There are three sources of error: the terms that are ignored, the roundings in the computation of \(z_3\) and \(c\) and the terms not kept in VSEB. A naive analysis gives:

\[
\begin{align*}
|\epsilon_0| &:= |x_1y_2 + x_2y_1 + x_2y_2| \\
&\leq 2(2u^2 - 2u^3)(2u^2 - 2u^3) + 2(2u^2 - 2u^3)^2 \\
&\leq 8u^3 - 11.9u^4 \\
|\epsilon_1| &:= |(z_{10}^+ + x_0y_2) - z_{3,1}| \\
&\leq \ulp(z_{10}^+ + x_0y_2) \\
&\leq \ulp(2u^2 + 4u^2) \\
&\leq 4u^3 \\
|\epsilon_2| &:= |(z_{00}^+ + x_2y_0) - z_{3,2}| \\
&\leq 4u^3 \\
|\epsilon_3| &:= |(z_{3,1} + z_{3,2}) - z_3| \\
&\leq 8u^3 \\
|\epsilon_4| &:= |(b_2 + x_1y_1) - c| \\
&\leq 4u^3 \\
|\epsilon_5| &:= |(z_{00}^+ + b_0 + b_1 + c + z_3) - (r_0 + r_1 + r_2)| \\
&\leq (2u^3 + 4.2u^4)|z_{00}^+ + b_0 + b_1 + c + z_3| \\
\end{align*}
\]

Yet, \(\bar{x}, \bar{y} \geq 1 - (2u^2 - 2u^3) - (2u^2 - 2u^3) \geq 1 - 2u\) so \(\bar{x}, \bar{y} \geq 1 - 4u\). We eventually obtain that the error cannot
be too large if $\epsilon_5 \neq 0$ (not detailed here, but similar to the proof of Theorem 11), and finally:

\[
\left| \frac{\bar{r} - \bar{y}}{xy} \right| \leq \frac{28u^3 - 11.9u^4}{1 - 4u} \leq 28u^3 + 107u^4
\]

This bound is very tight. Indeed, for instance for binary64, if we take:

\[
x_0, x_1, x_2 = 1 + (13 \cdot 2^{26} + 28)u, 2u - 2^{27}u^2, 2u^2 - 4u^3
\]
\[
y_0, y_1, y_2 = 1 + 7 \cdot 2^{27}u, 2u - (2^{28} - 8)u^2, 2u^2 - 4u^3
\]

we obtain a relative error around $(28 - 10^{-5})u^3$. 

6.5 Faster version

In this version, $e_4$ is not computed.

Algorithm 10 – $3\text{Prod}^{\text{fast}}_{5,3}(x_0, x_1, x_2, y_0, y_1, y_2)$. (38 operations & 1 test)

Require: $x$ and $y$ TW ; $p \geq 6$

Ensure: $\bar{r}$ TW and $\left| \frac{\bar{r} - \bar{y}}{xy} \right| \leq 44u^3 + 176u^4$

[same 5 first lines as 9]

$z_{3,1} \leftarrow \text{RN}(z_{10}^+ + x_0y_2)$ (FMA)

$z_{3,2} \leftarrow \text{RN}(z_{01}^+ + x_0y_2)$ (FMA)

$z_3 \leftarrow \text{RN}(z_{3,1} + z_{3,2})$

$s_3 \leftarrow \text{RN}(c + z_3)$

$e_0, e_1, e_2, e_3 \leftarrow \text{VecSum}(z_{00}^+, b_0, b_1, s_3)$

$r_0 \leftarrow e_0$

$r_1, r_2 \leftarrow \text{VSEB}(2)(e_1, e_2, e_3)$

This saves 8 operations and 1 test. Correctness is still ensured for the same reasons, provided that $p \geq 6$. Concerning the error bound, the proof is similar (in fact, simpler) than for the previous algorithm, so we omit it, and we obtain

\[
\left| \frac{\bar{r} - \bar{y}}{xy} \right| \leq \frac{44u^3 - 11.9u^4}{1 - 4u} \leq 44u^3 + 176u^4
\]

This bound is very tight, because the same input as for the previous version gives a relative error around $(44 - 10^{-5})u^3$.

7 PRODUCT OF a DW WITH a TW

To compute the product of a DW with a TW, we use the same algorithms as previously, slightly simplified using $x_2 = 0$. Additionally to being interesting in itself, this operation will be used to compute reciprocals and quotients, which justifies a detailed analysis.

Algorithm 11 – $3\text{Prod}^{\ast}_{5,3}(x_0, x_1, y_0, y_1, y_2)$. (45 operations & 2 tests)

Require: $x$ DW and $y$ TW ; $p \geq 6$

Ensure: $\bar{r}$ TW and $\left| \frac{\bar{r} - \bar{y}}{xy} \right| \leq 10.5u^3 + 39u^4$

[same 5 first lines as 9]

$z_{3,1} \leftarrow \text{RN}(z_{10}^+ + x_0y_2)$ (FMA)

$z_{3,2} \leftarrow \text{RN}(z_{01}^+ + x_0y_2)$ (FMA)

$z_3 \leftarrow \text{RN}(z_{3,1} + z_{3,2})$

$s_3 \leftarrow \text{RN}(c + z_3)$

$e_0, e_1, e_2, e_3, e_4 \leftarrow \text{VecSum}(z_{00}^+, b_0, b_1, c, z_3)$

$r_0 \leftarrow e_0$

$r_1, r_2 \leftarrow \text{VSEB}(2)(e_1, e_2, e_3, e_4)$

7.1 Estimates of the different terms

We suppose WLOG that $1 \leq x_0, y_0 < 2$, so that $|x_1| \leq u$, $|y_1| < 2u$ and $|y_2| < 2u^2$. Then:

\[
\frac{1}{2} \leq z_{00}^+ - 4u
\]

\[
|z_{00}^-| \leq 2u ; \quad u = z_{00}^+ \geq 2u^2
\]

\[
|z_{10}^+| < 4u
\]

\[
|z_{10}^-| < 2u
\]

\[
|z_{01}^+| < 2u
\]

\[
|z_{01}^-| < 2u
\]

\[
|z_{3,1}| < 5u^2
\]

\[
|z_{3,2}| < 7u^2
\]

\[
|s_3| \leq 13u^2
\]

7.2 Correctness and number of operations

Given this is a particular case of the previous algorithm, correctness is directly ensured, provided that $p \geq 6$.

Compared to the previous algorithm, we saved 1 operation, so that the total is 41.

7.3 Bound on the error

Theorem 11. If $x$ DW and $y$ TW, then the relative error committed by $3\text{Prod}^{\ast}_{5,3}(x, y)$ is bounded by $10.5u^3 + 39u^4$, provided that $p \geq 6$.

Proof: The new naive error analysis gives:

\[
|\epsilon_0| := |x_1y_2| \leq 2u^3 - 2u^4
\]

\[
|\epsilon_1| := |(z_{10}^+ + x_0y_2) - z_{3,1}| \leq 4u^3
\]

\[
|\epsilon_3| := |(z_{3,1} + z_{01}^-) - z_3| \leq 4u^3
\]

\[
|\epsilon_4| := |(b_2 + x_1y_1) - c| \leq 4u^3
\]

\[
|\epsilon_5| := |(z_{00}^+ + b_0 + b_1 + c + z_3) - (r_0 + r_1 + r_2)| \leq (2u^3 + 4.2u^4)|z_{00}^+ + b_0 + b_1 + c + z_3|
\]

We get $|\epsilon_0 + \cdots + \epsilon_4| \leq 14u^3 - 2u^4$, and finally

\[
|\frac{\bar{r} - \bar{y}}{xy}| \leq \frac{(2u^3 + 4.2u^4) + (14u^3 - 2u^4) + (10.5u^3 + 39u^4)}{1 - 4u}
\]

\[
\leq 16u^3 + 62u^4
\]

* First, we distinguish cases depending on whether $xy$ is significantly larger than 1 or not.

- We suppose that $|\epsilon_1| < 2u^4$. Then, given $|z_{10}^+| \leq u^2$, we must have $|x_0y_2| > 3u^2$ so $|z_0| > 1.5$, so that $xy \geq 1.5 - 5u$.

- We suppose that $|\epsilon_4| > 2u^4$. -
Then, given $|x_1y_1| \leq 2u^2$, we must have $|b_2| > 2u^2$ so $|z_1^* + z_0^*| > 4u$. This gives $x_0(2u - 2u^2) + y_0u \geq 4u$, so that $x_0y_0 \geq 1.5$ and $xy \geq 1.5 - 5a$.

Thus $xy \geq 1.5 - 5a$ (instead of $1 - 4a$) or $|e_1|, |e_4| \leq 2u^3$ (instead of $4u^3$ each).

* Then, we suppose $e_5 \neq 0$. By P-nonoverlapping, $r$ covers at least $3p$ bits, so this implies that one of the $e_i$ is not divisible by $2u^3\text{ulp}(r_0)$.

- We suppose that $\text{ulp}(r_0) \geq 2$. Then by P-nonoverlapping we must have $r \geq 2 - 4u$ so by the naive error bound $xy \geq 2 - 5u$.

- We suppose that $\text{ulp}(r_0) \leq 1$.

Then we must have a number among $z_{00}^*, z_{01}^*, z_{10}^*, c$ and $z_4$ that is not divisible by $2u^3$, so in particular whose absolute value is strictly smaller than $u^2$.

- We have seen that $z_{00}^*$ and $z_{01}^*$ are always divisible by $4u^2$.

- If $|z_{01}^*| < u^2$, then $|x_1| < u^2$ so $|e_0| \leq 2u^4$ (instead of $2u^3 - 2u^4$).

- If $|z_{10}^*| < u^2$, then $|y_1| < u^2$ so $|e_2| < u^3$ so $|e_0| \leq u^4$ (instead of $2u^3 - 2u^4$).

- If $|z_4| < u^2$, then $|e_3| \leq \frac{1}{2}u^3$ (instead of $4u^3$).

* Finally, we are left with several cases:

- Case $xy \geq 2 - 5a$. Then
  $$\frac{|r - xy|}{xy} \leq \frac{2u^3 + 4.2u^4 + (14u^3 - 2u^4)(1 + 2u^3 + 4.2u^4)}{2 - 5u} \leq 10u^3$$

- Case $2 - 5a > xy \geq 1.5 - 5a$ and $e_5 = 0$. Then
  $$\frac{|r - xy|}{xy} \leq \frac{14u^3 - 2u^4}{1.5 - 5u} \leq \frac{14u^3 - 2u^4}{1.5 - 5u}$$

- Case $2 - 5a > xy \geq 1.5 - 5a$ and $e_5 \neq 0$. Then
  $$\frac{|r - xy|}{xy} \leq \frac{2u^3 + 4.2u^4 + (12u^3 + 4.2u^4)(1 + 2u^3 + 4.2u^4)}{1.5 - 5u} \leq 10u^3 + 34u^4$$

- Case $1.5 - 6a > xy$ and $e_5 = 0$. Then
  $$\frac{|r - xy|}{xy} \leq \frac{10u^3 - 2u^4}{1 - 4u} \leq \frac{10u^3 + 41u^4}{1 - 4u}$$

- Case $1.5 - 6a > xy$ and $e_5 \neq 0$. Then (the worst case being the one where only $|c| < u^2$, because it is partially redundant with what $1.5 - 6a > xy$ gives)
  $$\frac{|r - xy|}{xy} \leq \frac{2u^3 + 4.2u^4 + (8.5u^3 - 2u^4)(1 + 2u^3 + 4.2u^4)}{1 - 4u} \leq 10.5u^3 + 39u^4$$

7.4 Faster version

Algorithm 12 – 3Prod_{fast}(x_0, x_1, y_0, y_1, y_2). (37 operations & 1 test)

Require: $x$ DW and $y$ TW ; $p \geq 6$

Ensure: $r$ TW and $\left|\frac{r - xy}{xy}\right| \leq 18u^3 + 75u^4$

[same 5 first lines as 9]

This bound is very tight, because the same input as for the previous version gives a relative error around $(18 - 2 \cdot 10^{-6})u^3$.

8 Reciprocal of a TW

To compute the reciprocal of a TW, we use Algorithm 13 below, which is based on Newton-Raphson iteration, following the idea of [7]. This algorithm requires the stronger constraint $p \geq 10$. For computing $1/x$, the Newton-Raphson iteration is

$$r_{n+1} = r_n(2 - r_nx)$$

which ensures a quadratic convergence towards $\frac{1}{x}$ as soon as $r_0$ is close enough to $1/x$ because

$$\left|\frac{r_{n+1} - \frac{1}{x}}{\frac{1}{x}}\right| \leq \left|\frac{r_n - \frac{1}{x}}{\frac{1}{x}}\right|^2.$$
8.1 Computation of $h^n$

Algorithm 13 uses $1 + \text{ulp}(1)$ instead of 1 to start the calculations in order to take profit from the following lemma:

**Lemma 12.** For any FP number $x$, $\text{RN}(x \times \text{RN}(\frac{1+2u}{x})) = 1 + 2u$.

**Proof:** Denote $a := \text{RN}(\frac{1+2u}{x})$, which can WLOG be assumed to be in $1, 2$. If $a \in [1 + 4u, 2]$, then we conclude using

$$|\text{RN}(xa) - (1 + 2u)| \leq (1 + 2u) \left( \frac{n}{1+u} + \frac{n}{1+5u} + \frac{n^2}{(1+u)(1+9u)} \right) < 2u$$

Thus, we are left with only $x \in \{1 - 2u, 1 - u, 1, 1 + 2u\}$, which are easily treated separately. \qed

Thus in Algorithm 13, one has to imagine a “virtual” $\bar{h}_0 = 2 - (1 + \text{ulp}(1)) = 1 - \text{ulp}(1)$.

8.2 Bound on the error

Momentarily, the computation of $\bar{i}$ is seen as a black box (see Section 8.3). We have

$$|a - \frac{1}{x_0}| \leq |a - \frac{1 + 2u}{x_0}| + \frac{1 + 2u}{x_0} - \frac{1}{x_0|} \leq u \left( \frac{1+2u}{x_0} + \frac{2u}{x_0} \right) \leq (3u + 2u^2) \frac{1}{x_0},$$

which implies $|\frac{1 - 3u}{x_0} a| \leq |a| \leq \frac{1 + 3u}{x_0}$, so that $|h_1| \leq (1 + u)(u|a|x_0| + |a| \cdot 2u|x_0|) \leq 3u + 13u^2$. Now,

$$\left| a - \frac{1}{x_0 + x_1} \right| = \left| a - \frac{1}{x_0 + x_1} \right| \frac{1 - \frac{x_0 + x_1}{x_0}}{x_0 + x_1} \leq (2u - 2u^2) \frac{1}{x_0 + x_1},$$

$$\left| a - \frac{1}{x_0 + x_1} \right| \leq 3u^2 + 13u^3,$$

$$\left| \frac{1}{x_0 + x_1} \right| \leq \frac{1 + 6u}{x_0 + x_1},$$

$$\left| h - (2 - a(x_0 + x_1)) \right| = \left| h_1 - (h_{1,1} - ax_1) \right| \leq |h_1| + |h_{1,1} - ax_1| \leq 3u^2 + 13u^3,$$

$$\left| a - h \right| = \left| b_1,1 - (b_1,1 + ah_1) \right| \leq |b_1,1,1 + ah_1| \leq u |b_1,1 - ah_1| \leq u (u |a| (1 - 2u) + |ah_1|) \leq (4u^2 + 11u^3) |a|,$$

$$\left| b - \frac{1}{x_0 + x_1} \right| \leq (7u^2 + 24u^3) |a| + (25u^2 + 61u^3) \frac{1}{x_0 + x_1} \leq (32u^2 + 121u^3) \frac{1}{x_0 + x_1}.$$
We have very precise information about Algorithm 15 – 3Prod\textsuperscript{\textit{fast}}(b_0, b_1, x_0, x_1, x_2). (44 operations & 2 tests)

\begin{align*}
    &z_{00}^+ z_{00}^- \leftarrow 2\text{Prod}(b_0, x_0) \\
    &z_{01}^+ z_{01}^- \leftarrow 2\text{Prod}(b_0, x_1) \\
    &z_{10}^+ z_{10}^- \leftarrow 2\text{Prod}(b_1, x_0) \\
    &b_0, b_1, b_2 \leftarrow \text{VecSum}(z_{00}, z_{01}, z_{10}) \\
    &c \leftarrow \text{RN}(b_0 + b_1 z_1) \text{ (FMA)} \\
    &z_{3,1} \leftarrow \text{RN}(z_{10} + b_1 x_1) \text{ (FMA)} \\
    &s_1, e_2, e_3, e_4 \leftarrow \text{VecSum}(-b_0', -b_1', -c, -z_3) \\
    &i_1, i_2 \leftarrow \text{VSEB}(2)(e_1, e_2, e_3, e_4)
\end{align*}

8.4 Computation of \(\vec{y}\)

We have very precise information about \(\vec{i}\), so we use a modified version of the fast algorithm.

Algorithm 15 - 3Prod\textsuperscript{\textit{fast}}(b_0, b_1, (1), i_1, i_2). (20 operations)

\begin{align*}
    &z_{01}^+ z_{01}^- \leftarrow 2\text{Prod}(b_0, i_1) \\
    &b_0, b_1 \leftarrow \text{Fast2Sum}(b_1, z_{01}) \\
    &z_{3,1} \leftarrow \text{RN}(z_{01} + b_1 i_1) \text{ (FMA)} \\
    &z_3 \leftarrow \text{RN}(z_{3,1} + b_1 i_2) \text{ (FMA)} \\
    &s_3 \leftarrow \text{RN}(b_1 + z_3) \\
    &e_0, e_1, e_2 \leftarrow \text{VecSum}(b_0, b_0', s_3) \\
    &y_0 \leftarrow e_0 \\
    &y_1, y_2 \leftarrow \text{Fast2Sum}(e_1, e_2)
\end{align*}

Remark 8. In \text{VecSum}(b_0, b_0', s_3), the sum of \(b_0'\) and \(s_3\) is performed with a 2Sum in order to ensure correctness, but we can still use a Fast2Sum for the second one.

A Fast2Sum can be used for the sum of \(b_1\) and \(z_{01}\) because if the condition for Fast2Sum to be errorless is not satisfied, this means that \(b_1\) is very small, so that the global error will be small anyway.

Given the estimates on \(\vec{i}\), basically all errors are negligible, except the one when computing \(s_3\). We get:

\[
    \left| \frac{\vec{y} - \vec{b}}{\vec{b}} \right| \leq \frac{u^3 + 256u^4}{(1 - 2u)(1 - 35u^2)}
\]

Thus we can take \(\delta_2 = u^3 + 260u^4\).

8.5 Final error bound and number of operations

If we use the accurate version for the first 3Prod\textsubscript{2,3}, then we can use \(\delta_1 = 10.5u^3 + 39u^4\) and finally obtain

Theorem 13. If \(\vec{x}\) is a TW, then the relative error committed by 3Rece\textsuperscript{\textit{acc}}(\vec{x}) is bounded by 11.5u^3 + 1465u^4, provided that \(p \geq 10\).

The total cost is 73 operations and 2 tests. If we use the fast version, then we can use \(\delta_1 = 18u^3 + 75u^4\) and finally obtain

Theorem 14. If \(\vec{x}\) is a TW, then the relative error committed by 3Rece\textsuperscript{\textit{fast}}(\vec{x}) is bounded by 19u^3 + 1502u^4, provided that \(p \geq 10\).

The total cost is 65 operations and 1 test.

9 Quotient of two TW

In this section, we also assume \(p \geq 10\). In order to compute \(\vec{z}/\vec{x}\), we could simply compute the product of \(\vec{z}\) and the reciprocal of \(\vec{x}\). However, this would mean that we compute something like \(\vec{z} \times (\vec{b} \times (2 - \vec{b} \vec{x}))\), while it is significantly better to compute \((\vec{z} \vec{b}) \times (2 - \vec{b} \vec{x})\).

Indeed, this allows to parallelize the computations of \(\vec{z} \vec{b}\) and \((2 - \vec{b} \vec{x})\), and the optimizations allowed by the constraints on \(i\) are more efficiently used when multiplying by a TW rather than by a DW.

Algorithm 16 - 3Div(z_0, z_1, z_2, x_0, x_1, x_2). (119 operations & 4 tests, resp. 103 operations & 2 test)

Require: \(\vec{z}, \vec{x}\) TW; \(p \geq 10\)

Ensure: \(\vec{y}\) TW and \(|\vec{y}/\vec{z}|\leq 24u^3 + 1509u^4\), resp. 39u^3 + 1582u^4

\begin{align*}
    &\vec{z} \leftarrow 2 - 3\text{Prod}_{2,3}(\vec{b}, \vec{x}) \\
    &\vec{y} \leftarrow 3\text{Prod}_{3,3}(\vec{a}, i)
\end{align*}

For the computation of \(2 - \vec{b} \vec{x}\), the same algorithm and error bound as previously are used. For the computation of \(\vec{z} \vec{b}\), 3Prod\textsubscript{2,3} is used (the relative error is denoted by \(\delta_3\)). For the computation of the final product, algorithm 17 is used.

Algorithm 17 - 3Prod\textsuperscript{\textit{fast}}(a_0, a_1, a_2, (1), i_1, i_2). (21 operations)

\begin{align*}
    &z_{01}^+ z_{01}^- \leftarrow 2\text{Prod}(a_0, i_1) \\
    &b_0, b_1 \leftarrow \text{Fast2Sum}(a_1, z_{01}^+) \\
    &z_{3,1} \leftarrow \text{RN}(z_{01} + a_1 i_1) \text{ (FMA)} \\
    &z_{3,2} \leftarrow \text{RN}(z_{3,1} + a_0 i_2) \text{ (FMA)} \\
    &z_3 \leftarrow \text{RN}(z_{3,2} + b_1') \\
    &s_3 \leftarrow \text{RN}(z_3 + a_2) \\
    &e_0, e_1, e_2 \leftarrow \text{VecSum}(b_0, b_0', s_3) \\
    &y_0 \leftarrow e_0 \\
    &y_1, y_2 \leftarrow \text{Fast2Sum}(e_1, e_2)
\end{align*}

The error analysis is similar to the one of Algorithm 15 with an additional 2u^3, and we get

\[
    \left| \frac{\vec{y} - \vec{a}}{\vec{a}} \right| \leq \frac{3u^3 + 256u^4}{(1 - 2u)(1 - 35u^2)} \leq 3u^3 + 264u^4.
\]

Globally, we have,

\[
    \left| \frac{\vec{y}}{\vec{z}} \right| \leq \left( (\delta_1 + \delta_2 + \delta_3)(1 + 70u^2) + 1165u^4 \right) \left| \frac{\vec{z}}{\vec{x}} \right|
\]

If we use the accurate versions, then we can use \(\delta_1 = 10.5u^3 + 39u^4 = \delta_2\), and we finally obtain
Theorem 15. If \( \bar{x}, \bar{z} \) are TW, then the relative error committed by 3Div\textsuperscript{acc}(\bar{x}, \bar{z}) is bounded by \( 24u^3 + 1509u^4 \), provided that \( p \geq 10 \).

The total cost is 119 operations and 4 tests. If we use the fast versions, then we can use \( \delta_1 = 18u^3 + 75u^4 = \delta_3 \) and finally obtain

Theorem 16. If \( \bar{x}, \bar{z} \) are TW, then the relative error committed by 3Div\textsuperscript{fast}(\bar{x}, \bar{z}) is bounded by \( 39u^3 + 1582u^4 \), provided that \( p \geq 10 \).

The total cost is 103 operations and 2 tests.

10 Square root of a TW

In this section, we assume \( p \geq 11 \). To compute the square root of a TW, we use Algorithm 18 below, based again on the Newton-Raphson iteration. Its analysis and the optimizing tricks are very similar to the ones used before for division. The underlying iteration is now

\[
r_{n+1} = r_n(1.5 - \frac{1}{2}r^2_n),
\]

which ensures a quadratic convergence towards \( \frac{1}{\sqrt{x}} \) as soon as \( r_0 \) is close enough to \( \sqrt{x} \), because

\[
\left| r_{n+1} - \frac{1}{\sqrt{x}} \right| = \frac{1}{2} \sqrt{x}(r_n\sqrt{x} + 2) \left| r_n - \frac{1}{\sqrt{x}} \right|^2
\]

Algorithm 18 – 3SqRt\((x_0, x_1, x_2)\). (127 operations & 4 tests, resp. 111 operations & 2 tests)

Require: \( \bar{x} \) TW ; \( p \geq 11 \)

Ensure: \( \bar{y} \) TW and \( \left| \bar{y} - \frac{1}{\sqrt{x}} \right| \leq 24u^3 + 10260u^4 \), resp. \( 39u^3 + 10333u^4 \)

\[
a \leftarrow \text{RN} \left( (1 + 2\text{ulp}(1))/\text{RN}(\sqrt{x_0}) \right)
\]

\[
a' = \frac{1}{2}a \text{ (exact)}
\]

\[
h_0^{(1)}, h_1^{(1)} \leftarrow 2\text{Prod}(a, x_0)
\]

\[
h_1^{(1)} \leftarrow \text{RN}(-h_1^{(1)} - ax_1) \text{ (FMA)}
\]

\[
h_0^{(2)}, h_1^{(2)} \leftarrow 2\text{Prod}(a', h_0^{(1)})
\]

\[
h_1^{(2)} \leftarrow 1.5 - h_0^{(2)} \text{ (exact)}
\]

\[
h_1^{(2)} \leftarrow \text{RN}(-h_1^{(2)} - a'h_1^{(1)}) \text{ (FMA)}
\]

\[
b_{0,1}, b_{1,1} \leftarrow 2\text{Prod}(a, h_0^{(2)})
\]

\[
b_{1,2} \leftarrow \text{RN}(b_{1,1} + ah_1^{(2)}) \text{ (FMA)}
\]

\[
\bar{b} \leftarrow \text{Fast2Sum}(b_{0,1}, b_{1,2})
\]

\[
\bar{b}' = \frac{1}{2}\bar{b} \text{ (exact)}
\]

\[
\bar{i}^{(1)} \leftarrow 3\text{Prod}_{2,3}(\bar{b}, \bar{x})
\]

\[
\bar{i}^{(2)} \leftarrow 1.5 - 3\text{Prod}_{2,3}(\bar{b}', \bar{i}^{(1)})
\]

\[
\bar{y} \leftarrow 3\text{Prod}_{3,3}(\bar{i}^{(1)}, \bar{i}^{(2)})
\]

The computation of \( h_0^{(2)} \) is exact because \( h_0^{(2)} \geq 0.5 \) (this is why we started with \( 1 + 2\text{ulp}(1) \) instead of 1).

The computation of \( i^{(1)} \) is performed with a 3Prod\textsuperscript{2,3} algorithm (relative error bounded by \( \delta_1 \)).

The computation of \( i^{(2)} \) is performed using Algorithm 14 (or its fast version), where the penultimate line is replaced by \( e_1 \leftarrow \text{Fast2Sum}(5)(-z_{39}, s_1) \) (relative error bounded by \( \delta_3 \)). This works provided that \( p \geq 11 \).

The computation of \( \bar{y} \) is performed using Algorithm 17 (relative error bounded by \( \delta_3 = 3u^3 + 263u^4 \)).

We obtain

\[
\left| \bar{y} - \frac{1}{\sqrt{x}} \right| \leq \left( \delta_1(1.5 + 287u^2) + \delta_2(0.5 + 123u^2) + \delta_3(1 + 162u^2) + 9916u^4 \right) \sqrt{x}
\]

so that,

Theorem 17. If \( \bar{x} \) is a TW, then the relative error committed by 3SqRt\textsuperscript{acc}(\bar{x}) (resp. 3SqRt\textsuperscript{fast}(\bar{x})) is bounded by \( 24u^3 + 10260u^4 \) (resp. \( 39u^3 + 10333u^4 \)).

The total cost is 127 operations and 4 tests (resp. 111 operations and 2 tests).

11 Comparison with general expansions \((n = 3)\)

The algorithms presented in this paper can be compared to the “general” floating-point expansion algorithms (in the special case \( n = 3 \)), and to the algorithms related presented in [20].

11.1 Sum

The algorithm used is the same, but using P-nonoverlapping instead of ulp-nonoverlapping roughly divides the error in the worst case by 4.

11.2 Product

Many more terms are sought in the general algorithms, so that the relative error is bounded by only around \( 8u^3 \). Still, if we have in mind the implementation of correctly rounded elementary functions, our bounds will, in general, be far enough.

The cost of the general algorithms is around twice larger than ours: 88 operations and 2 tests for the “quick-and-dirty” algorithm, assuming that “Renormalize” can be used.

11.3 Reciprocal, division and square root

Our algorithms cannot be fairly compared with Newton-Raphson based algorithms, because they are designed for a number of terms being a power of 2.

Concerning the “paper-and-pencil” method for division, using it with our algorithms (for instance the accurate versions) for sum and product costs around 150 operations and gives a relative error around \( 2^9 u^3 \). It is
clearly possible to improve these figures, but probably not enough to compete with the algorithm we proposed. It is anyway significantly better than what Priest proposes in [22, page 116], where he provides $7265$ as a bound for the number of operations, and $\approx 2^{13}u^3$ for the relative error.

12 Conclusion
We have shown that usual floating-point expansion algorithms adapted for building and adding triple word numbers are correct in the context of triple words, and we have introduced algorithms for rounding, multiplying, reciprocating, dividing and computing square roots of triple word numbers, along with correctness proofs and error bounds.

Some bounds have been shown to be tight, but this is not the case for $2^{\text{Prod}_{\text{32},\text{32}}}$, and for the reciprocal, division and square root algorithms, so the error bounds on these algorithms may be improved.

The natural continuation of this paper would be to suggest additional algorithms that would make TW arithmetic efficiently compatible with general expansions: for instance, adding a TW with a quad-word number to arithmetic efficiently compatible with general expansions: for instance, adding a TW with a quad-word number to

12 References