On-The-Fly Range Reduction

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On-the-fly Range Reduction

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Abstract: In several cases, the input argument of an elementary function evaluation is given bit-serially, most significant bit first. We suggest a solution for performing the first step of the evaluation (namely, the range reduction) *on the fly*: the computation is overlapped with the reception of the input bits. This algorithm can be used for the trigonometric functions $\sin$, $\cos$, $\tan$ as well as for the exponential function.

Key-words: Range reduction, Elementary functions, Computer arithmetic.

(Résumé : tsvp)

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Réduction d’argument “au vol”

Résumé : Il arrive que l’opérande dont on doit calculer une fonction élémentaire soit disponible chiffre après chiffre, en série, en commençant par les poids forts. Nous proposons une solution permettant d’effectuer la première phase de l’évaluation (la réduction d’argument) *au vol*: le calcul et la réception des chiffres d’entrée se recouvrent. Cet algorithme peut être utilisé pour les fonctions trigonométriques $\sin$, $\cos$, $\tan$, ainsi que pour l’exponentielle.

Mots-clé : Réduction d’argument, fonctions élémentaires, arithmétique des ordinateurs.

1 Introduction

The algorithms used for evaluating the elementary functions only give a correct result if the argument is within some bounded interval. To evaluate an elementary function $f(x)$ (sine, cosine, exponential,...) for any x, one must find some "transformation" that makes it possible to deduce $f(x)$ from some value $g(y)$, where

- y, called the *reduced argument*, is deduced from x;
- y belongs to the convergence domain of the algorithm implemented for the evaluation of g.

With the usual functions, the only cases for which reduction is not straightforward are the cases where y is equal to $x - nC$, where n is an integer and C a constant (for instance, for the trigonometric functions, C is a multiple of $\pi/8$).

Example 1 (Computation of the cosine function) *Assume that we want to evaluate* $\cos(x)$*, and that the convergence domain of the algorithm used to evaluate the sine and cosine of the reduced argument contains* $[0, +\pi/4]$. *We choose* $C = \pi/4$*, and the computation of* $\cos(x)$ *is decomposed in three steps:*

- *compute* y *and* n *such that* $y \in [0, +\pi/4]$ *and* $y = x - n\pi/4$;
- *compute* $g(y, n) =$

$$\begin{cases} \cos(y) & \text{if} \quad n \bmod 8 = 0 \\ \frac{\sqrt{2}}{2}\left(\cos(y) - \sin(y)\right) & \text{if} \quad n \bmod 8 = 1 \\ -\sin(y) & \text{if} \quad n \bmod 8 = 2 \\ -\frac{\sqrt{2}}{2}\left(\cos(y) + \sin(y)\right) & \text{if} \quad n \bmod 8 = 3 \\ -\cos(y) & \text{if} \quad n \bmod 8 = 4 \\ \frac{\sqrt{2}}{2}\left(-\cos(y) + \sin(y)\right) & \text{if} \quad n \bmod 8 = 5 \\ \sin(y) & \text{if} \quad n \bmod 8 = 6 \\ \frac{\sqrt{2}}{2}\left(\cos(y) + \sin(y)\right) & \text{if} \quad n \bmod 8 = 7 \end{cases} \tag{1}$$

- *obtain* $\cos(x) = g(y, n)$.

Example 2 (Computation of the exponential function) *Assume that we want to evaluate* e^x *in a radix-2 number system, and that the convergence domain of the algorithm used to evaluate the exponential of the reduced argument contains* $[0, \ln(2)]$. *We can choose* $C = \ln(2)$*, and the computation of* e^x *is then decomposed in three steps:*

- *compute* $y \in [0, \ln(2)]$ *and* n *such that* $y = x - n\ln(2)$*;*
- *compute* $g(y) = e^y$*;*
- *compute* $e^x = 2^n g(y)$.

Unless multiple-precision arithmetic is used during the intermediate calculations, a straightforward computation of y as $x - nC$ is to be avoided, since this operation will lead to catastrophic cancellations (i.e., to very inaccurate estimates of y) when x is large or close to an integer multiple of C. Many algorithms have been suggested for performing the range reduction accurately [1, 2, 3, 9, 11].

Now, there are many cases (on special-purpose systems) where the input argument of a calculation is generated most significant digit first. This happens, for instance, when this argument is the result of a division or a square root obtained through a digit-recurrence algorithm [7, 10], the output of an on-line algorithm [5, 12], or when it is generated by an analog-to-digital converter.

In the sequel of this paper, we present an adaptation of the Modular Range Reduction Algorithm [3, 8] that accepts such digit serial inputs and performs the range reduction "on the fly": most of the computation is overlapped with the reception of the input bits, and the reduced argument is produced almost immediately after reception of the last input bit. On-the-fly arithmetic algorithms have already been proposed by Ercegovac and Lang for rounding or converting a number from redundant to non-redundant representation [4, 6].

2 Notations

In the sequel of the paper, $x = x_h x_{h-1} \cdots x_0 . x_{-1} x_{-2} \cdots x_\ell$ is the input argument, $C = 0.C_{-1}C_{-2} \cdots C_{-p}$ is the constant of the range reduction (with $-p \leq \ell$), and $y = 0.y_{-1}y_{-2} \cdots y_{-p}$ is the reduced argument. We assume $1/2 \leq C < 1$. These values satisfy:

- $0 \leq y < C$;
- $n = (x - y)/C$ is an integer.

We also define, for each i, m_i (also called $2^i \bmod C$) as the unique value between 0 and C such that $(2^i - m_i)/C$ is an integer. These notations give some contraints on x and C (e.g., C is less than 1, x is less than 2^{h+1}). One can easily adapt the algorithms given in the sequel of the paper to variables belonging to other domains. We chose these contraints to make the presentation of the algorithms simpler.

3 Non-redundant algorithm

Algorithm 1 is by far less efficient than the "redundant" algorithm given afterwards. We give it because it is simpler to understand, and because the other algorithm is derived from it. The basic idea is the following: at step i of the algorithm, when we receive input bit x_{h-i} of x, we add $x_{h-i} \times \left(2^i \bmod C\right)$ to an accumulator. If the accumulated value becomes larger than C, we subtract C from it.

Let us call A_{i+1} the value obtained after this operation. One can easily check that $0 \leq A_{i+1} < C$ and $A_{i+1} - x_h x_{h-1} \cdots x_{h-i} \times 2^{h-i}$ is an integer multiple of C. Hence the final value stored in the accumulator is equal to the reduced argument y.

Algorithm 1 Non-redundant algorithm.

$A_0 = 0$
for $i = 0$ **to** $h - \ell$ **do**
  $T_i = A_i + x_{h-i} m_{h-i}$
  if $T_i < C$ **then**
    $A_{i+1} = T_i$
  else
    $A_{i+1} = T_i - C$
$y = A_{h-\ell+1}$

A possible variant consists in computing $U_i = A_i + x_{h-i}\,(m_{h-i} - C)$ in parallel with T_i, and then to choose A_{i+1} equal to U_i if $U_i \geq 0$, otherwise T_i.

4 Redundant algorithm

Now, to accelerate the reduction, we assume that we perform the accumulations with *carry-save* additions. The carry-save number system allows very fast, carry-free additions. On the other hand, its intrinsic redundancy makes comparisons somewhat more complex. The accumulator will store the values A_i in carry-save. In the previous algorithm, we needed "exact" comparisons between the A_i's and C. Having the A_i's stored in carry-save makes these "exact" comparisons difficult. Instead of that, we will perform comparisons based on the examination of the first three carry-save positions of A_i only. This will not allow to bound the A_i's by C. Nevertheless, we will show that the A_i's will be upper-bounded by

$C + \frac{1}{2}$ (therefore by $\frac{3}{2}$), which will suffice for our purpose. We denote:

$$A_i = \Big((A_{i,0}^{(1)}, A_{i,0}^{(2)}); (A_{i,-1}^{(1)}, A_{i,-1}^{(2)}); (A_{i,-2}^{(1)}, A_{i,-2}^{(2)}); \ldots; (A_{i,-p}^{(1)}, A_{i,-p}^{(2)})\Big)$$

where $A_{i,j}^{(1)}$ and $A_{i,j}^{(2)}$ are in $\{0,1\}$ and

$$A_i = \sum_{j=0}^{p} (A_{i,j}^{(1)} + A_{i,j}^{(2)}) \cdot 2^{-j}.$$

The variable T_i of the non-redundant algorithm is used again, and is also represented in carry-save form:

$$T_i = \Big((T_{i,0}^{(1)}, T_{i,0}^{(2)}); (T_{i,-1}^{(1)}, T_{i,-1}^{(2)}); (T_{i,-2}^{(1)}, T_{i,-2}^{(2)}); \ldots; (T_{i,-p}^{(1)}, T_{i,-p}^{(2)})\Big)$$

This gives algorithm 2.

Algorithm 2 Redundant algorithm.

$A_0 = 0 + 1$
for $i = 0$ **to** $h - \ell$ **do**
  $T_i = A_i +_{\text{cs}} x_{h-i}\, m_{h-i}$
  $\widehat{T}_i = \Big((T_{i,0}^{(1)}, T_{i,0}^{(2)}); (T_{i,-1}^{(1)}, T_{i,-1}^{(2)}); (T_{i,-2}^{(1)}, T_{i,-2}^{(2)})\Big) - 1$
    converted to non-redundant binary using a 3-bit adder
  if $\widehat{T}_i < C$ **then**
    $A_{i+1} = T_i$
  else
    $A_{i+1} = T_i -_{\text{cs}} C$ (or $T_i +_{\text{cs}} (1 - C) - 1$)
$B = A_{h-\ell+1} +_{\text{cs}} (1 - C)$
Convert $A_{h-\ell+1}$ and B to non-redundant binary.
if $B < 2$ **then**
  $y = A_{h-\ell+1} - 1$
else
  $y = B - 2$

In the loop, we do not want to waste time with a full comparison to know whether we need to subtract C from T_i or not. Thus we use a rough approximation $\widehat{T}_i$ to T_i based on the first three digits of T_i. Since

$$\Big((T_{i,-3}^{(1)}, T_{i,-3}^{(2)}); \ldots; (T_{i,-p}^{(1)}, T_{i,-p}^{(2)})\Big) \le 2 \cdot 2^{-3} + 2 \cdot 2^{-4} + \cdots + 2 \cdot 2^{-p} < \frac{1}{2},$$

we have:

$$\widehat{T_i} \leq T_i < \widehat{T_i} + \frac{1}{2}$$

We want to ensure that A_i is always positive, that is, $T_i - C$ does not lead to a negative number. Then, the subtraction is performed only when $\widehat{T_i} \geq C$. In this case, $T_i - C \geq \widehat{T_i} - C \geq 0$.

Now, we want to find an upper bound on all the A_i's (and one on the T_i's). Suppose that for a given i, we have $A_i \leq M$. Thus $T_i \leq M + C$. If $\widehat{T_i} < C$, then $A_{i+1} = T_i < \widehat{T_i} + \frac{1}{2} < C + \frac{1}{2}$; otherwise, $A_{i+1} = T_i - C \leq M$. If we choose $M = C + \frac{1}{2}$, then $A_{i+1} \leq M$ in both cases. By induction, $A_i \leq C + \frac{1}{2}$ and $T_i \leq 2C + \frac{1}{2}$ for all i.

The final value of y is converted to non-redundant representation using a conventional (i.e., non-redundant) addition. Another, faster, solution is to convert it on-the-fly, during the second loop of the algorithm, using Ercegovac and Lang's on-the-fly algorithm [4, 6] for conversion from redundant to non-redundant representation.

5 An example: computation of $\cos(1010.111)$.

We choose $C = \pi/4 \approx 0.1100101$ ($p = 7$). Since $x = 1010.111$, we have $h = 3$ and $\ell = -3$).

The values of the m_i's are:

$$\left\{\begin{array}{lllll} m_3 & = & 2^3 & \bmod \pi/4 & \approx & 0.0010011 \\ m_2 & = & 2^2 & \bmod \pi/4 & \approx & 0.0001001 \\ m_1 & = & 2^1 & \bmod \pi/4 & \approx & 0.0110111 \\ m_0 & = & 2^0 & \bmod \pi/4 & \approx & 0.0011011 \\ m_{-1} & = & 2^{-1} & \bmod \pi/4 & = & 0.1 \\ m_{-2} & = & 2^{-2} & \bmod \pi/4 & = & 0.01 \\ m_{-3} & = & 2^{-3} & \bmod \pi/4 & = & 0.001 \end{array}\right.$$

The carry-save representations of the variables T_i and A_i generated by the redundant algorithm are

$x_3 = 1$	$T_0 = \begin{cases} 1.0010011 \\ 0.0000000 \end{cases}$	$0 < C$	$A_0 = \begin{cases} 1.0010011 \\ 0.0000000 \end{cases}$
$x_2 = 0$	$T_1 = \begin{cases} 1.0010011 \\ 0.0000000 \end{cases}$	$0 < C$	$A_1 = \begin{cases} 1.0010011 \\ 0.0000000 \end{cases}$
$x_1 = 1$	$T_2 = \begin{cases} 1.0100100 \\ 0.0100110 \end{cases}$	$0.1 < C$	$A_2 = \begin{cases} 1.0100100 \\ 0.0100110 \end{cases}$
$x_0 = 0$	$T_3 = \begin{cases} 1.0000010 \\ 0.1001000 \end{cases}$	$0.1 < C$	$A_3 = \begin{cases} 1.0000010 \\ 0.1001000 \end{cases}$
$x_{-1} = 1$	$T_4 = \begin{cases} 1.0001010 \\ 1.0000000 \end{cases}$	$1 \geq C$	$A_4 = \begin{cases} 1.0010001 \\ 0.0010100 \end{cases}$
$x_{-2} = 1$	$T_5 = \begin{cases} 1.0100101 \\ 0.0100000 \end{cases}$	$0.1 < C$	$A_5 = \begin{cases} 1.0100101 \\ 0.0100000 \end{cases}$
$x_{-3} = 1$	$T_6 = \begin{cases} 1.0010101 \\ 0.1000000 \end{cases}$	$0.1 < C$	$A_6 = \begin{cases} 1.0010101 \\ 0.1000000 \end{cases}$

We then get $y = 0.1010101$, whereas the exact value of $x \bmod \pi/4$ is $0.10101010001\ldots$.

6 Conclusion

The redundant algorithm presented in Section 4 allows fast, on-the-fly, range reduction. The accuracy of this method is the same as that of the Conventional Modular range reduction method (see [3, 8]).

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