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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

*Evaluating signs of determinants using  
single-precision arithmetic*

Francis Avnaim , Jean-Daniel Boissonnat , Olivier Devillers , Franco P. Preparata ,  
Mariette Yvinec

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image  
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## Evaluating signs of determinants using single-precision arithmetic

Francis Avnaim<sup>\*</sup>, Jean-Daniel Boissonnat<sup>\*\*</sup>, Olivier Devillers<sup>\*\*\*</sup>,  
Franco P. Preparata<sup>\*\*\*\*</sup>, Mariette Yvinec<sup>\*\*\*\*\*</sup>

Programme 4 — Robotique, image et vision

Projet Prisme

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**Abstract:** We propose a method to evaluate signs of  $2 \times 2$  and  $3 \times 3$  determinants with  $b$ -bit integer entries using only  $b$  and  $(b + 1)$ -bit arithmetic respectively. This algorithm has numerous applications in geometric computation and provides a general and practical approach to robustness. The algorithm has been implemented and experimental results show that it slows down the computing time by only a small factor with respect to floating-point calculation.

**Key-words:** Computational geometry, Exact arithmetic, Precision

*(Résumé : tsvp)*

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## **Evaluation du signe d'un déterminant en arithmétique simple précision**

**Résumé :** Nous proposons une méthode d'évaluation du signe des déterminants  $2 \times 2$  et  $3 \times 3$  dont les éléments sont des entiers représentés sur  $b$  bits en utilisant respectivement une arithmétique sur  $b$  et  $b+1$  bits. Cet algorithme a de nombreuses applications pour les calculs géométriques et constitue un moyen pratique et général d'obtenir des programmes robustes. L'algorithme a été implanté et les résultats expérimentaux montrent que le temps de calcul n'est augmenté que d'un facteur raisonnable par rapport au calcul en arithmétique flottante.

**Mots-clé :** Géométrie algorithmique, Arithmétique exacte, Précision

## 1 Introduction

Most decisions in geometric algorithms are based on signs of determinants. For example, deciding if a point belongs to a given halfspace or a given ball reduces to evaluating the sign of a determinant. Moreover, such evaluations are often the only numerical parts of the entire algorithm. Therefore, it is crucial to have reliable answers to such tests.

This observation relates to the very model of Computational Geometry, whose assumption is that geometric parameters are real numbers and that arithmetic operations are performed with infinite precision. Obviously, such assumption does not hold when algorithms are translated into computer programs, where the parameters are represented either as integers or as floating-point numbers. Floating-point implementations, although naively a reasonable approach to real-number arithmetic, have been shown to have serious shortcomings, since they may cause not only numerical errors but also fatal membership errors (such as inclusion of a point in an interval to which it does not belong, etc.).

This difficulty has received some deserved attention in recent years (see, e.g., [For89, GY86, HHK89, Mil88a, Mil88b, Mil89, GSS89, SI88]) and several approaches have been proposed on how to obviate the shortcoming. The common objective is to produce *robust* algorithms, namely algorithms whose answer is a (small) perturbation of the correct answer (as produced by the infinite-precision algorithm). As noted by Fortune [For89], there are basically two categories of approaches to this objective: The most common one resorts to approximate (i.e., rounded) computations, and uses properties of the assumed primitives to establish the topological correctness of the results (i.e., robustness) (see, e.g., [For89, For92, FM91, HHK89, GSS89]). The other uses exact (i.e., integer) computations, but, since multiprecision integer arithmetic is required ( $d$ -fold for a dimension  $d \times d$  determinant), a straightforward implementation of this approach has a large performance penalty (see [FV93] for a detailed analysis). Significant improvements over the naive method have been recently obtained. In particular, a promising approach consists in combining multiprecision integer (or rational) arithmetic and a floating point filter based on interval analysis [KLN91, FV93, BJMM93].

Our approach falls in the exact integer arithmetic category and our objective is to use as few bits as possible to evaluate signs of determinants. Typically, we will use no more bits than the number  $b$  of bits used to code the entries. This implies that

we would not do multiplications of the entries and, *a fortiori*, we would not compute any determinants when we evaluate the signs.

To the best of our knowledge, the only related attempt has been made by Clarkson [Cla92]. Clarkson uses an adaptation of the Gram-Schmidt procedure for computing an orthogonal basis, and employs approximate arithmetic. For a  $d \times d$  determinant with  $b$ -bit integer entries, Clarkson's algorithm runs in time  $O(d^3b)$  and uses  $2b + 1.5d$  bits to represent the values. Our algorithm is quite different. It is limited to  $2 \times 2$  and  $3 \times 3$  determinants and its asymptotic worst-case complexity is worse than that of Clarkson. However, it is simpler, it uses respectively  $b$  and  $(b + 1)$ -bit representations, and extensive simulations have shown that it performs well in practice. Since the most common applications are two- and three-dimensional, our method is competitive in this range of parameters.

The paper is organized as follows. In Section 2, we shall discuss the two-dimensional case in detail, both because it provides insights for the three-dimensional case and because it is used to resolve the determination of the sign of a three-dimensional determinant in Section 3. In Section 4, we present some significant applications of the outlined technique in computational geometry. In Section 5, we compare our technique with a straightforward computation using floating point arithmetic and discuss the experimental results.

## 2 Two-dimensional case

### 2.1 The algorithm

Let  $D = \begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix}$  be a  $2 \times 2$  determinant whose entries are  $b$ -bit integers.

If one of the four entries is zero,  $D$  reduces to the product of two integers and the sign of  $D$  follows from the sign of the two integers. In the rest of this section, we assume that all four entries are nonzero.

Without loss of generality, we may assume that all the entries are strictly positive. Indeed, if an odd number of entries are negative, then the sign of  $D$  is trivially obtained. If two entries are negative, either they belong to the same row or the same column, in which case changing their sign changes the sign of  $D$ , or they belong to a diagonal, in which case changing their sign does not change  $D$ . If all entries are negative, changing their sign does not change  $D$ .

Furthermore, we may assume without loss of generality that  $x_2 \geq x_1$  and  $y_2 \geq y_1$ . The case where  $x_2 < x_1$  and  $y_2 < y_1$  can be transformed to the previous one by exchanging the two rows of the matrix, which yields a change of the sign of  $D$ . In the other cases, the sign of  $D$  can be obtained readily; specifically, if  $x_1 \leq x_2$  and  $y_2 < y_1$ ,  $D < 0$ , and, if  $x_1 > x_2$  and  $y_2 \geq y_1$ ,  $D > 0$ .

Under the above assumptions, we can write:

$$x_2 = x_1 k_1 + x_r \text{ with } k_1 \in \mathbb{N} \text{ and } 0 \leq x_r < x_1$$

and define:

$$y_r = y_2 - k_1 y_1$$

Then

$$D = \begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix} = \begin{vmatrix} x_1 & y_1 \\ x_2 - k_1 x_1 & y_2 - k_1 y_1 \end{vmatrix} = \begin{vmatrix} x_1 & y_1 \\ x_r & y_r \end{vmatrix}$$

If  $y_1 > \frac{2^b}{k_1}$  then  $y_r$  cannot be computed, but in that case  $y_r$  is certainly negative and thus  $D < 0$ . If  $y_r$  can be computed but is outside the range  $[0, y_1]$  the sign of  $D$  can be obtained too: if  $y_r < 0$  then  $D < 0$  and if  $y_r > y_1$  then  $D > 0$ . Moreover, if  $x_r < \frac{x_1}{2}$  and  $y_r > \frac{y_1}{2}$ , then  $D > 0$ , and if  $x_r > \frac{x_1}{2}$  and  $y_r < \frac{y_1}{2}$ , then  $D < 0$ . Otherwise we rewrite  $D$  as follows:

$$\begin{aligned} \text{if } x_r < \frac{x_1}{2} \text{ and } y_r < \frac{y_1}{2} \text{ then } D &= \begin{vmatrix} x_1 & y_1 \\ x_r & y_r \end{vmatrix} \\ \text{if } x_r > \frac{x_1}{2} \text{ and } y_r > \frac{y_1}{2} \text{ then } D &= \begin{vmatrix} x_1 & y_1 \\ x_1 - x_r & y_1 - y_r \end{vmatrix} \end{aligned}$$

In both cases, we get a new determinant where both entries of the second row have been divided by at least two, and we can iterate the computation.

In conclusion, at each iteration, using only comparisons and euclidean divisions, either the algorithm stops or it iterates on a reduced problem, where a row is replaced by one whose entries are less than half the size of the original ones. Hence, the number of iterations is bounded from above by the logarithm of the largest representable integer, i.e. the number  $b$  of bits in the binary representation of the initial entries.

We sum up the results in the following theorem.



**Theorem 1** *Let  $D$  be a  $2 \times 2$  determinant with  $b$ -bit integer entries. There exists an algorithm that evaluates the sign of  $D$  using only  $b$ -bit arithmetic. The algorithm requires at most  $b$  iterations, each iteration involving  $O(1)$  additions/subtractions, comparisons and euclidean divisions.*

### 3 Three dimensions

#### 3.1 Geometric intuition

Let  $D = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}$  be a  $3 \times 3$  determinant with  $b$ -bit integer entries. Vector  $(x_i, y_i, z_i)$  is denoted  $U_i$  and the unit vectors along the three axis will be denoted  $E_x, E_y$  and  $E_z$ . The  $z$  direction is called *vertical* and  $u$  denotes the vertical projection of vector  $U$  onto the horizontal plane  $z = 0$ . For convenience, we will often identify a vector  $U$  with the point whose coordinate vector is  $U$ . Without loss of generality, we can assume that the  $z_i$  are nonnegative and that  $z_3 \geq z_1, z_2$ .

The basic idea is as follows : unless the sign of  $D$  can be directly assessed, we replace the original matrix with a matrix having the *same determinant*, but provably smaller entries. This assures that the evaluation will terminate. The basic device used is the standard addition to a row of a linear combination of the other rows.

More specifically, assume (here and in Sections 3.1-3.6), that the projections  $u_1, u_2$  of  $U_1, U_2$  are noncolinear (i.e. independent) vectors. This implies that the three vectors  $U_1, U_2$  and  $E_z$  are linearly independent, and we can express  $U_3$  as

$$U_3 = \kappa_1 U_1 + \kappa_2 U_2 + \kappa_3 E_z \tag{1}$$

where  $\kappa_1, \kappa_2, \kappa_3 \in \mathbb{R}$ . It follows that

$$D = \kappa_3 \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ 0 & 0 & 1 \end{vmatrix}. \tag{2}$$

Hence, if the sign of  $\kappa_3$  is known, the problem is reduced to evaluating the sign of

$$\begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix},$$

and we are faced with a 2-dimensional problem.

We now show that, in some (usually most) cases, the sign of  $\kappa_3$  can be determined. We have:

$$\kappa_3 = z_3 - \kappa_1 z_1 - \kappa_2 z_2. \quad (3)$$

Let  $\kappa_1 = k_1 + \rho_1$ ,  $\kappa_2 = k_2 + \rho_2$ , with  $k_1 = \lfloor \kappa_1 \rfloor$ ,  $k_2 = \lfloor \kappa_2 \rfloor$  and  $0 \leq \rho_1, \rho_2 < 1$ . We define

$$R = U_3 - k_1 U_1 - k_2 U_2.$$

Then, Equation 3 becomes

$$\kappa_3 = z_R - \rho_1 z_1 - \rho_2 z_2.$$

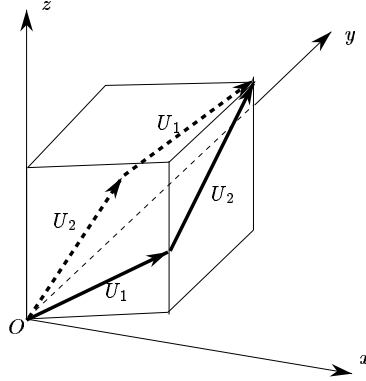
If  $z_R < 0$ , then  $\kappa_3 < 0$  since  $z_1$  and  $z_2$  are nonnegative, and, if  $z_R > z_1 + z_2$ ,  $\kappa_3 > 0$ . Otherwise,  $R$  lies in the intersection  $\mathcal{B}$  of the cylinder projecting along the  $z$  axis onto the parallelepiped  $u_1 \oplus u_2$  ( $\oplus$  denoting the Minkowski sum) with the slab of points  $W$  such that  $0 \leq z_W \leq z_1 + z_2$  (see Figure 1). In this case, we still do not know the sign of  $\kappa_3$ , but we can write:

$$D = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_R & y_R & z_R \end{vmatrix} \quad (4)$$

where the row with largest  $z$  component has been replaced by  $R$ .

The following geometric interpretation of our definitions will be useful in the sequel. Let  $H$  be the plane passing through  $O$  and spanned by  $U_1$  and  $U_2$ . The vectors  $U_1$  and  $U_2$  generate in  $H$  the lattice  $\mathcal{L}_H = \{l_1 U_1 + l_2 U_2, l_1, l_2 \in \mathbb{Z}\}$ .  $\mathcal{L}_H$  projects vertically onto the lattice  $\mathcal{L}$  of the horizontal plane generated by  $u_1$  and  $u_2$ . To each cell  $\mathcal{C} = \{(l_1 + \varepsilon_1)u_1 + (l_2 + \varepsilon_2)u_2, 0 \leq \varepsilon_1, \varepsilon_2 \leq 1\}$  of  $\mathcal{L}$ , we associate its *reference point*  $l_1 u_1 + l_2 u_2$ . In particular,  $k_1 u_1 + k_2 u_2$  is the reference point of the cell of  $\mathcal{L}$  that contains  $u_3$ . To each cell of  $\mathcal{L}$ , we associate also a *box*. The box associated to the cell  $\mathcal{C}$  of  $\mathcal{L}$  with reference point  $l_1 u_1 + l_2 u_2$  is a copy of  $\mathcal{B}$  translated by vector  $l_1 U_1 + l_2 U_2$  which projects vertically onto  $\mathcal{C}$ . Let  $\mathcal{IB}$  be the union of these boxes, i.e. the translated copies of  $\mathcal{B}$  by the vectors  $l_1 U_1 + l_2 U_2$  for  $l_1, l_2 \in \mathbb{Z}$ .  $\mathcal{IB}$  contains plane  $H$  and can be considered as an approximation of  $H$ .

The geometric interpretation of the above discussion is now: if  $U_3$  lies above (below)  $\mathcal{IB}$ ,  $\kappa_3$  is positive (negative), and otherwise,  $U_3$  can be replaced by a vector contained in  $\mathcal{B}$ .

Figure 1: Box  $\mathcal{B}$ .

### 3.2 The algorithm

The algorithm consists of  $O(b)$  iterations, but may terminate earlier. Each iteration consists of three steps.

During a *preliminary step*, described in Subsection 3.3, the vectors whose  $z$  components are negative are replaced by the opposite vectors and some easy cases are solved.

The *first step*, described in Subsection 3.4, determines whether  $U_3$  lies below  $\mathcal{IB}$ , above  $\mathcal{IB}$ , or inside some box of  $\mathcal{IB}$ . In the first two cases,  $D$  reduces to a  $2 \times 2$  determinant with  $b$ -bit integer entries : its sign can be evaluated using the algorithm of Section 2. In the last case, we translate point  $U_3$  in a direction parallel to  $H$  to obtain  $R = U_3 - k_1 U_1 - k_2 U_2 \in \mathcal{B}$ . However, we cannot simply iterate on the vectors  $(U_1, U_2, R)$ . Indeed, although  $R$  is known to lie in box  $\mathcal{B}$ , the binary representation of its components may require as many as  $b + 1$  bits. Furthermore, the  $z$  component  $z_R$  of  $R$  only satisfies  $0 \leq z_R \leq z_1 + z_2$ , which does not imply that this component is smaller than the original  $z_3$ .

The *second step* of the algorithm, to be described in Subsection 3.6, will either evaluate the sign of  $\kappa_3$  or find a vector  $R' = R + \theta_1 U_1 + \theta_2 U_2$  ( $\theta_1, \theta_2 \in \{-1, 0, +1\}$ ) such that the encoding length of its  $x$  and  $y$  components does not exceed  $b$ , and its  $z$  component is less than  $z_3/2$ .

The algorithm is then iterated on the vectors  $(U_1, U_2, R')$ . Now, a reduction by two of the modulus of the maximum  $z$  component of the vectors in  $D$  is guaranteed after at most three iterations. Hence, in total, at most  $3b$  iterations will be required to either find that  $D = 0$  or end up with a  $2 \times 2$  determinant.

### 3.3 Preliminary step

As in the two-dimensional case, the sign of the determinant can be evaluated readily in some cases. First, we multiply by  $-1$  the rows whose  $z$  component are negative so that all the entries of the last column are non-negative. This does not change  $D$  if no or two rows are concerned and changes  $D$  to  $-D$  otherwise. Secondly, we permute the rows so that  $U_3$  has the largest  $z$  component.

Then, if the three minors  $\begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix}$ ,  $\begin{vmatrix} x_2 & y_2 \\ x_3 & y_3 \end{vmatrix}$  and  $\begin{vmatrix} x_3 & y_3 \\ x_1 & y_1 \end{vmatrix}$  are all strictly positive (negative) then  $D$  is positive (negative). Geometrically, this case corresponds to the situation where  $u_1$ ,  $u_2$  and  $u_3$  span positively the horizontal plane, or, equivalently, the origin lies inside the triangle  $u_1u_2u_3$ .

### 3.4 First step: computing $R$

The first step of each iteration either determines the sign of  $\kappa_3$  or, when  $U_3$  lies in  $\mathcal{B}$ , computes the vector  $R = U_3 - k_1U_1 - k_2U_2$ . This is not an obvious task since the moduli of the integers  $k_1$  and  $k_2$  can be as big as  $2^{2b+1}$  : indeed,  $k_1 = \lfloor \kappa_1 \rfloor$  and  $k_2 = \lfloor \kappa_2 \rfloor$  and it follows from (1) that

$$\kappa_1 = \frac{\begin{vmatrix} x_3 & y_3 \\ x_2 & y_2 \end{vmatrix}}{\begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix}} \text{ and } \kappa_2 = \frac{\begin{vmatrix} x_3 & y_3 \\ x_1 & y_1 \end{vmatrix}}{\begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix}}$$

As we will restrict ourselves to  $(b+1)$ -bit arithmetic (a full discussion of that point will be given in Section 3.5), we may not be able to compute the  $k_i$ .

Consider again the lattice  $\mathcal{L}$  in the horizontal plane generated by  $u_1$  and  $u_2$ . As vector  $U_3$  has  $b$ -bit integer components, the coordinates of the points of the line segments  $OU_3$  and  $Ou_3$  have moduli less than  $2^b$ .

Informally, our strategy to compute  $R$  is to probe a subset of  $O(b)$  edges of the lattice  $\mathcal{L}$  crossed by  $Ou_3$ . For each such edge, we consider the corresponding edge in lattice  $\mathcal{L}_H$ . If the  $z$  range of all edges encountered during the process remain inside the bounds of the available  $(b+1)$ -bit arithmetic, the procedure ends when the cell containing  $u_3$  is found. If, on the contrary, an encountered edge of  $\mathcal{L}_H$  belongs to a box whose  $z$  range exceeds the  $(b+1)$ -bit representation, the  $z$  range of this edge extends entirely outside the bounds of the  $b$ -bit representation. In such a case, the sign of  $\kappa_3$  can be determined easily and the calculation of  $R$  is halted.

We now present the details of the procedure.

**Substep 1.1.** Consider the parallelogram formed by the union of the four lattice cells  $\mathcal{C}_0, \mathcal{C}_0 - u_1, \mathcal{C}_0 - u_2, \mathcal{C}_0 - (u_1 + u_2)$ , where  $\mathcal{C}_0$  is the Minkowski sum  $u_1 \oplus u_2$ . The boundary of this parallelogram consists of eight cell edges. By a straightforward (three-step) binary search we determine which of these edges is intersected by the half-line  $L$  issued from  $O$  and containing  $u_3$ , the search discriminant being the sign of a  $2 \times 2$  determinant of the form  $\begin{vmatrix} u_3 \\ w \end{vmatrix}$  where  $w \in \{u_1, u_2, u_1 + u_2, u_1 - u_2\}$ . This search also identifies which of the cells  $\mathcal{C}_0, \mathcal{C}_0 - u_1, \mathcal{C}_0 - u_2, \mathcal{C}_0 - (u_1 + u_2)$  is intersected by the half-line  $L$ . Let  $\mathcal{C}'_0 = \mathcal{C}_0 - \epsilon_1 u_1 - \epsilon_2 u_2$  be such cell. Note that if any of the determinants  $\begin{vmatrix} u_3 \\ w \end{vmatrix}$  is equal to 0, then either  $k_1 = k_2$  or one of the  $k_i$ 's is 0. In such cases,  $R$  can be computed as in the two-dimensional case.

For the sake of simplicity, we standardize the problem by replacing the original basis  $(u_1, u_2)$  with the basis  $(v_1, v_2)$ , where  $v_i = (2\epsilon_i + 1)u_i, i = 1, 2$ . Denoting by  $c_u$  (resp.  $c_v$ ) the reference point of the cell  $\mathcal{C}$  of  $\mathcal{L}$  that contains  $u_3$  when we take  $(u_1, u_2)$  (resp.  $(v_1, v_2)$ ) as basis vectors of  $\mathcal{L}$ , we observe that

$$c_u = c_v + \epsilon_1 u_1 + \epsilon_2 u_2. \quad (5)$$

We shall in fact compute  $c_v$ , and then obtain  $c_u$  using (5). In the sequel,  $k'_1$  and  $k'_2$  will denote the coordinates of  $c_v$  in the basis  $(v_1, v_2)$ . Let  $D_i, i = 1, 2$ , be the line of the horizontal plane containing  $v_i$ .

**Substep 1.2.** Next, we have to test whether or not  $u_3$  belongs to cell  $\mathcal{C}'_0$ . This test entails locating  $u_3$  with respect to the edge traversed by the half-line  $L$ . i.e. locating  $u_3$  with respect to either  $D_1 + v_2$  or  $D_2 + v_1$ . In the first case, we evaluate the sign of  $\begin{vmatrix} v_1 \\ u_3 - v_2 \end{vmatrix}$  and, in the second, of  $\begin{vmatrix} u_3 - v_1 \\ v_2 \end{vmatrix}$  (if the sign is negative,  $u_3 \in \mathcal{C}'_0$ ). If

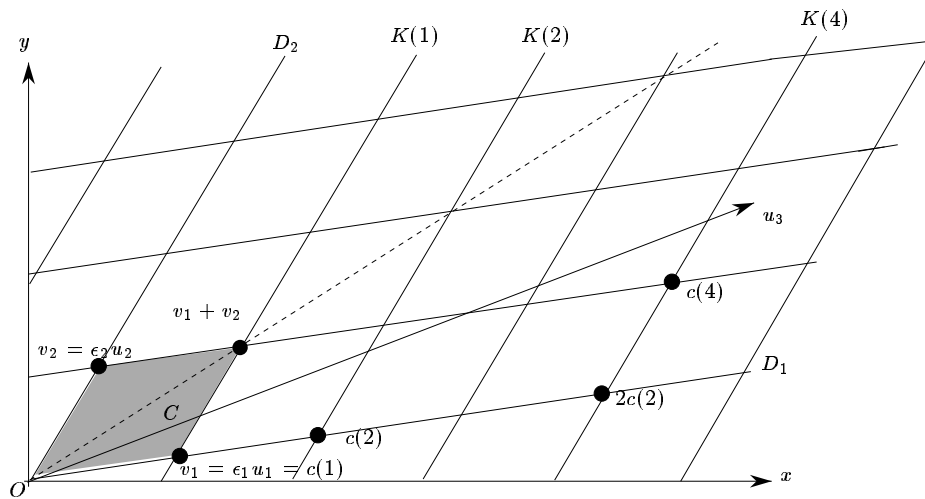


Figure 2: Illustration of Step 1.

$u_3$  is included in  $C'_0$ ,  $k'_1 = k'_2 = 0$ , we deduce  $c_u$  and the corresponding point  $C_u$  of  $\mathcal{L}_H$  using (5), compute  $R = U_3 - C$  and go to Substep 1.6. Otherwise, we proceed to Substep 1.3.

**Substep 1.3.** Let  $K(1)$  denote the first lattice line traversed by  $Ou_3$ , i.e.,  $K(1) \in \{D_1 + v_2, D_2 + v_1\}$ . Without loss of generality, here and hereafter, we assume  $K(1) = D_2 + v_1$  (see figure 2). For  $\lambda \in \mathbb{N}$ , we note  $K(\lambda)$  the line  $D_2 + \lambda v_1$ . The vertices of the edge of lattice  $\mathcal{L}$  belonging to  $K(\lambda)$  and intersected by  $Ou_3$  (if such an intersection exists) are denoted  $c(\lambda)$  and  $c(\lambda) + v_2$ . Notice that  $c(\lambda) = \lambda v_1 + \lambda' v_2$  for some  $\lambda' \in \mathbb{N}, 0 \leq \lambda' < \lambda$ .

In this substep, we will successively probe lines  $K(2), K(4), K(8), \dots$ . Each of these probes may yield the sign of  $\kappa_3$ , in which case the process will terminate. If not, the search will continue until the unique integer  $k$  is determined such that  $Ou_3$  intersects  $K(2^k)$  but not  $K(2^{k+1})$ . After completing the probe of  $K(2^j)$ , the algorithm will store in a stack  $S$  point  $c(2^j)$ . It is convenient to describe the search as a sequence of simpler actions detailed below.

**1.3.1.** Assume that  $c(2^{l-1})$  has been determined.  $Ou_3$  crosses the line  $K(2^{l-1})$  between  $c(2^{l-1})$  and  $c(2^{l-1}) + v_2$ . Let  $z'$  and  $z''$  be the  $z$  coordinates of the two corresponding points of the lattice  $\mathcal{L}_H$ ,  $|z' - z''| = z_2$ . If  $z'$  and  $z''$  are both negative, then  $\kappa_3 > 0$  and, if  $z'$  and  $z''$  are both greater than  $2^b$ , then  $\kappa_3 < 0$ ; in such cases, the sign of  $D$  is known and the algorithm halts. Otherwise  $z'$  and  $z''$  have both encoding lengths at most  $b + 1$ , and the process continues.

**1.3.2.** We test if  $Ou_3$  crosses the line  $K(2^l)$  by evaluating the sign of the  $2 \times 2$  determinant  $\Delta = \begin{vmatrix} u_3 - 2c(2^{l-1}) \\ v_2 \end{vmatrix}$ . Notice that  $2c(2^{l-1}) \in K(2^l)$ . If  $Ou_3$  does not intersect  $K(2^l)$  ( $\Delta < 0$ ), then we go to Substep 1.4. Otherwise, we compute  $c(2^l)$  as described in Substep 1.3.3.

**1.3.3.** Since  $Ou_3$  crosses  $K(2^{l-1})$  between  $c(2^{l-1})$  and  $c(2^{l-1}) + v_2$ ,  $Ou_3$  crosses  $K(2^l)$  between  $2c(2^{l-1})$  and  $2c(2^{l-1}) + 2v_2$ . Clearly  $c(2^l)$  is either  $2c(2^{l-1})$  or  $2c(2^{l-1}) + v_2$  (the latter in Figure 3). Point  $c(2^l)$  can be determined by testing on which side of  $Ou_3$  point  $2c(2^{l-1}) + v_2$  lies, i.e., by evaluating the sign of the  $2 \times 2$  determinant  $\begin{vmatrix} u_3 \\ 2c(2^{l-1}) + v_2 \end{vmatrix}$ .

Note that, if in Substep 1.3.2,  $u_3$  has been found to belong to  $K(2^l)$  ( $\Delta = 0$ , a “degenerate case”), then  $u_3$  has been located between  $K(2^l)$  and  $K(2^{l+1})$ . We then

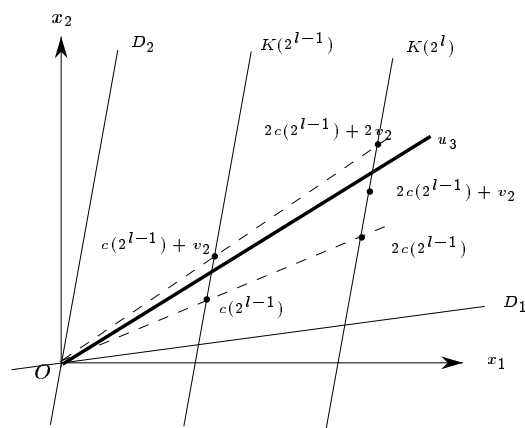


Figure 3: For Substep 1.3.3.

set  $\lambda_f = 2^l$  and proceed to Substep 1.5. Otherwise, the search continues through 1.3.1-1.3.3.

**Substep 1.4.** Assume now that  $Ou_3$  intersects the line  $K(2^k)$  but not the line  $K(2^{k+1})$ . Then the algorithm computes the integer  $\lambda$  such that  $Ou_3$  crosses  $K(\lambda)$  but not  $K(\lambda + 1)$  and sets  $\lambda_f = \lambda$ . The determination of  $\lambda$  is a binary search. This search involves  $k$  steps numbered  $k - 1, k - 2, \dots, 0$ . We denote  $\lambda_h$  the integer such that  $Ou_3$  intersects  $K(\lambda_h)$  but not  $K(\lambda_h + 2^h)$ . Assume that at the beginning of step  $h$ , we know  $\lambda_{h+1}$  and  $c(\lambda_{h+1})$ . We now explain how  $\lambda_h$  and  $c(\lambda_h)$  are inductively computed from  $\lambda_{h+1}$  and  $c(\lambda_{h+1})$ . The basis of the induction is given by  $h + 1 = k$  and  $\lambda_{h+1} = 2^k$ . Again, the search is better illustrated as a sequence of simpler actions.

**1.4.1** First, as in Step 1.3.1, let  $z'$  and  $z''$  be the  $z$  coordinates of the two points of the lattice  $\mathcal{L}_H$  corresponding to  $c(\lambda_{h+1})$  and  $c(\lambda_{h+1}) + v_2$ . If  $z'$  and  $z''$  are both negative, then  $\kappa_3 > 0$  and, if  $z'$  and  $z''$  are both greater than  $2^b$ , then  $\kappa_3 < 0$ ; in such cases, the sign of  $D$  is known and the algorithm halts. Otherwise  $z'$  and  $z''$  have both encoding lengths at most  $b + 1$ .

**1.4.2** The algorithm then determines on which side of  $K(\lambda_{h+1} + 2^h)$  point  $u_3$  lies, which can be done by evaluating the sign of the  $2 \times 2$  determinant  $\Delta' =$



$\left| \begin{array}{c} u_3 - c(\lambda_{h+1}) - c(2^h) \\ v_2 \end{array} \right|$ , where  $c(2^h)$  is popped out of stack  $S$ . If  $u_3$  lies on the same side of  $K(\lambda_{h+1} + 2^h)$  as  $O$  ( $\Delta' < 0$ ), then  $\lambda_{h+1} = \lambda_h$ ,  $c(\lambda_h) = c(\lambda_{h+1})$  and we can proceed to Step  $h - 1$ . Otherwise ( $\Delta' \geq 0$ ),  $\lambda_h = \lambda_{h+1} + 2^h$  and we have to compute  $c(\lambda_h)$ .

**1.4.3** It is to be observed that  $Ou_3$  crosses  $K(\lambda_h)$  between  $c(\lambda_{h+1}) + c(2^h)$  and  $c(\lambda_{h+1}) + c(2^h) + 2v_2$ . Thus  $c(\lambda_h)$  is either  $c(\lambda_{h+1}) + c(2^h)$  or  $c(\lambda_{h+1}) + c(2^h) + v_2$  depending on which side of  $Ou_3$  point  $c(\lambda_{h+1}) + c(2^h) + v_2$  lies, which is given by the sign of  $\left| \begin{array}{c} u_3 \\ c(\lambda_{h+1}) + c(2^h) + v_2 \end{array} \right|$ .

In the special case where, in Substep 1.4.2, we find  $\Delta' = 0$ , we set  $\lambda_f = \lambda_{h+1} + 2^h$  and proceed to Substep 1.5.

The search is carried on until one of the following occurs : the algorithm halts, or it goes to Substep 1.5 at an intermediate stage, or it performs all the steps  $k - 1, k - 2, \dots, 0$ . In the last case, we set  $\lambda_f = \lambda_0$  and go to Substep 1.5.

**Substep 1.5** This substep determines the cell of  $\mathcal{L}$  that contains  $u_3$ .  $u_3$  is known to belong to the parallelogram  $c(\lambda_f), c(\lambda_f) + v_1, c(\lambda_f) + v_1 + 2v_2, c(\lambda_f) + 2v_2$ . A last test locates  $u_3$  with respect to line  $D_1 + c(\lambda_f) + v_2$  and determines the cell  $\mathcal{C}$  of the lattice  $\mathcal{L}$  that contains  $u_3$ . More precisely, if  $\left| \begin{array}{c} u_3 - c(\lambda_f) - v_2 \\ v_1 \end{array} \right| \geq 0$ , then  $\mathcal{C}$  is the cell whose reference point is  $c(\lambda_f)$  in the  $(v_1, v_2)$  basis. Otherwise,  $\mathcal{C}$  is the cell whose reference point is  $c(\lambda_f) + v_2$ . The reference point  $c_u$  of  $\mathcal{C}$  in the  $(u_1, u_2)$  basis and the corresponding point  $C_u$  of  $\mathcal{L}_H$  are then obtained using (5) and we compute  $R = U_3 - C_u$ .

**Substep 1.6** If  $z_R < 0$ , then  $\kappa_3 < 0$  and, if  $z_R > z_1 + z_2$ , then  $\kappa_3 > 0$ . Otherwise, we go to Step 2.

This ends the description of the first major step of the algorithm. The vector  $r = u_3 - c_u$  belongs to the cell of  $\mathcal{L}$  whose reference point is  $O$ , thus the encoding lengths of  $x_R$  and  $y_R$  are at most  $b + 1$  and  $0 \leq z_R \leq z_1 + z_2$ .

### 3.5 Arithmetic

In this section, we show that  $(b + 1)$ -bit arithmetic is sufficient to run the above algorithm, assuming that  $U_1, U_2$  and  $U_3$  are  $b$ -bit integers.

First, we observe that all encountered  $c(\lambda)$  and  $c(\lambda) + v_2$  can be represented using  $b + 1$  bits. Indeed, since  $p = K(\lambda) \cap Ou_3$  belongs to the line segment  $Ou_3$ , the encoding length of its coordinates is less than the one of  $u_3$ , and since  $c(\lambda)$  belongs to the line segment  $p - u_2, p + u_2$ , one additional bit is enough to store  $c(\lambda)$ .

Next, we show that the computations of vector  $R$  performed in Steps 1.2 or 1.6 do not require more than  $(b + 1)$ -bit arithmetic. The computation of the  $x$  and  $y$ -components of  $R$  do not cause any problem since  $c_v, u_3 - c_v$  and  $u_3 - c_u$  can be represented with at most  $b + 1$  bits. Consider now the computation of  $z_R$ . Let  $z_v$  be the  $z$ -component of the point  $C_v$  of  $\mathcal{L}_H$  which corresponds to  $c_v$  and let  $z_u$  be the  $z$ -component of  $C_u$ . The bit-length of  $z_v$  is known to be at most  $b + 1$ , and it is easy to see from Equation (5) that the bit-length of  $z_u$  does not exceed the bit-length of  $z_v$ . If  $z_u$  is positive or negative with  $|z_u| < 2^b$ ,  $z_R = z_v - z_u$  can be computed using  $(b + 1)$ -bit arithmetic. If  $z_u$  is negative with  $|z_u| > 2^b$ , then  $z_R$  and  $\kappa_3$  are known to be negative and we do not need to compute  $z_R$ .

At last, we show that the signs of the determinants used in Steps 1.3.2, 1.3.3, 1.4.2 and 1.4.3 can be evaluated using  $(b + 1)$ -bit arithmetic. The vectors appearing in those determinants are combinations of  $u_1, u_2, u_3$  and some  $c(\lambda)$  : for instance, at Step 1.3.3, we need to compute  $2c(2^{l-1}) + v_2$ . It follows from the description of the algorithm that these vectors can always be computed using  $(b + 3)$ -bit arithmetic. We now explain how to reduce the number of bits of the arithmetic to  $b + 1$  for each of the Steps 1.3.2, 1.3.3, 1.4.2 and 1.4.3 of the algorithm.

**Step 1.3.2.** In this Step, we test on which side of  $K(2^l)$  point  $u_3$  lies. The problem arises when the coordinates of  $u_3 - 2c(2^{l-1})$  are not both representable with  $(b+1)$  bits. The idea is therefore to replace point  $2c(2^{l-1})$  with another point  $w$  of  $K(2^l)$  such that  $u_3 - w$  is represented with  $(b+1)$  bits. Let  $\mathcal{SP} \triangleq [-2^b, 2^b] \times [-2^b, 2^b]$  be the single precision domain. We claim that such construction can be accomplished if at least one of  $\{c(2^{l-1}), c(2^{l-1}) + v_2\}$  and at least one of  $\{c(2^{l-1}) - u_3, c(2^{l-1}) + v_2 - u_3\}$  belong to  $\mathcal{SP}$ . Let  $w_1$  and  $w_2 - u_3$  be points in  $\mathcal{SP}$  chosen from these two sets respectively. It follows that point  $-w_1 - (w_2 - u_3) = u_3 - (w_1 + w_2)$  is representable with  $(b+1)$  bits and that  $w_1 + w_2 \in K(2^l)$  since  $w_1, w_2 \in K(2^{l-1})$ . We conclude

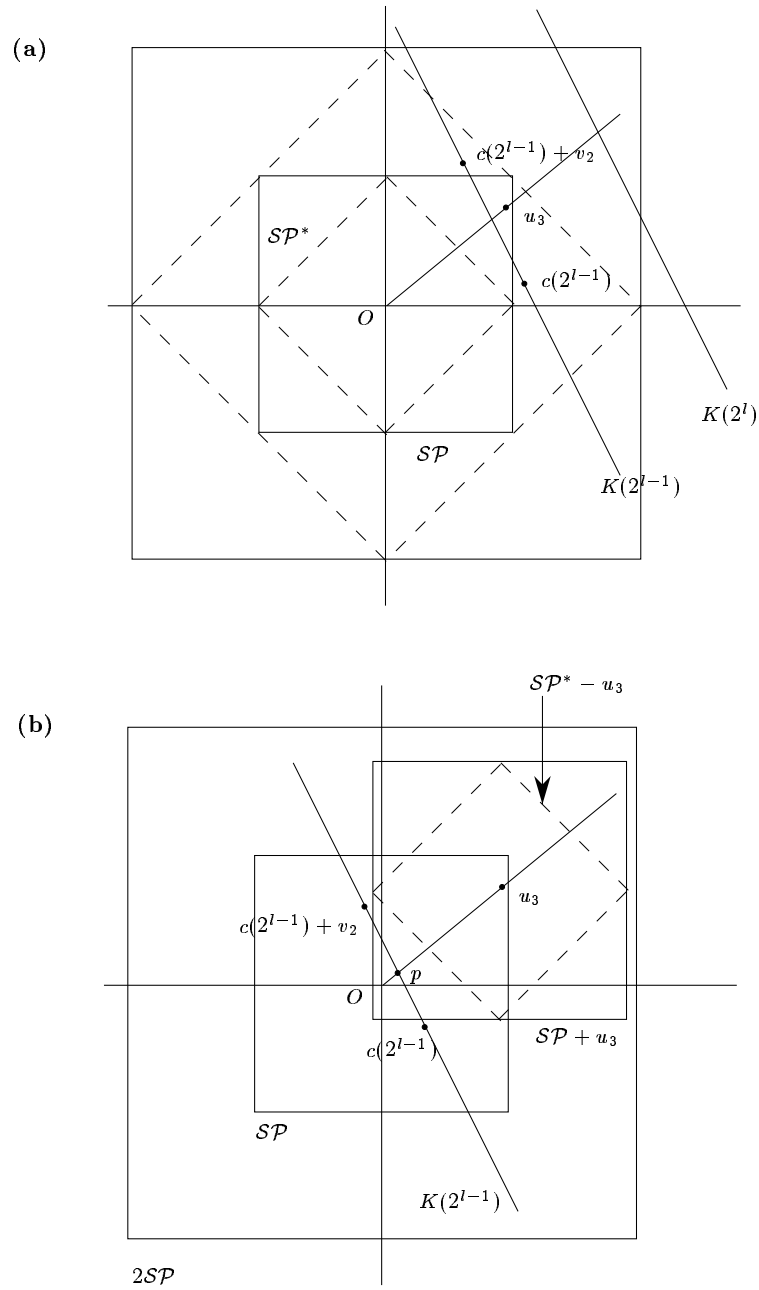


Figure 4: Illustrations for the cases : (a)  $c(2^{l-1}) \notin \mathcal{SP}$  and  $c(2^{l-1}) + v_2 \notin \mathcal{SP}$ , (b)  $c(2^{l-1}) - u_3 \notin \mathcal{SP}$  and  $c(2^{l-1}) + v_2 - u_3 \notin \mathcal{SP}$ .

that the entries of the determinant  $\begin{vmatrix} u_3 - w \\ v_2 \end{vmatrix}$  are representable with  $(b + 1)$  bits.

Otherwise we have the following easily decidable alternatives :

- (i)  $c(2^{l-1}) \notin \mathcal{SP}$  et  $c(2^{l-1}) + v_2 \notin \mathcal{SP}$ . We claim that  $u_3$  and  $O$  are on the same side of  $K(2^l)$ . Indeed, since  $v_2 \in \mathcal{SP}$ , the line  $K(2^{l-1})$  does not intersect the square  $\mathcal{SP}^*$  with vertices  $(0, \pm 2^b)$  and  $(\pm 2^b, 0)$  (see Figure 4a). Then  $K(2^l)$  is entirely outside the square  $2\mathcal{SP}^*$  which contains  $\mathcal{SP}$ .
- (ii)  $c(2^{l-1}) - u_3 \notin \mathcal{SP}$  and  $c(2^{l-1}) + v_2 - u_3 \notin \mathcal{SP}$ . We claim that  $u_3$  and  $O$  are on distincts sides of  $K(2^l)$ . Indeed, arguing as above, line  $K(2^{l-1})$  does not intersect the square  $\mathcal{SP}^* + u_3$  ( $\mathcal{SP}^*$  centered at  $u_3$ , see Figure 4b). Thus, if  $p$  is the intersection between  $K(2^{l-1})$  and  $Ou_3$ ,  $\|pu_3\|_\infty \geq \frac{1}{2} \|pu_3\|_1 > 2^{b-1}$  (since  $p$ , being external to  $\mathcal{SP}^* + u_3$ , has  $L_1$ -distance from  $u_3 > 2^b$ ). The point  $p' = 2p$  is the point where the lines  $Ou_3$  and  $K(2^l)$  intersect and we have :

$$\|Op'\|_\infty = 2 \|Op\|_\infty = 2 \|Ou_3\|_\infty - 2 \|pu_3\|_\infty < 2 \|Ou_3\|_\infty - 2^b \leq \|Ou_3\|_\infty,$$

which proves the claim.

**Step 1.4.2.** The modification of this step is similar to (and simpler than) that of

Step 1.3.2. Here we are led to the evaluation of the sign of  $\begin{vmatrix} u_3 - w \\ v_2 \end{vmatrix}$ , where point

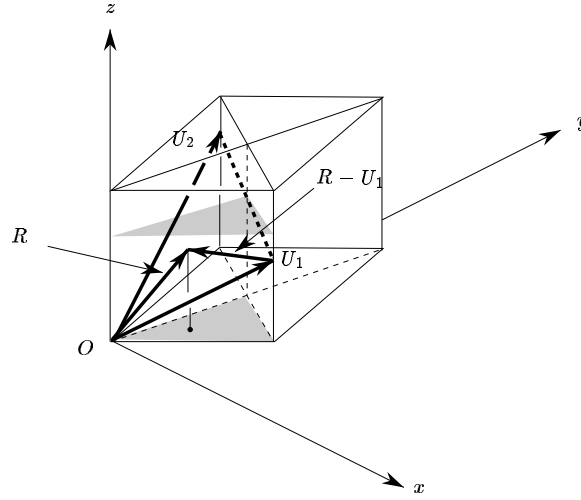
$w$  must be chosen on line  $K(\lambda_{h+1} + 2^h)$ . Since, as we already know,  $u_3$  and  $O$  are on distinct sides of  $K(2^{h+1})$ , one of  $c(2^h)$  and  $c(2^h) + v_2$  can be represented with  $b$  bits ; let  $w_1$  be this vector. Similary, since  $O$  and  $u_3$  are on the same side of  $K(2\lambda_{h+1})$ , one of  $c(\lambda_{h+1}) - u_3$  and  $c(\lambda_{h+1}) + v_2 - u_3$  can be represented with  $b$  bits ; let  $w_2 - u_3$  be this vector. The opposite of the sum of these two vectors  $-(w_1 + (w_2 - u_3)) = u_3 - (w_1 + w_2)$  is represented with  $(b + 1)$ -bits and  $w \stackrel{\Delta}{=} w_1 + w_2 \in K(\lambda_{h+1} + 2^h)$ , as we wished to show.

**Steps 1.3.3 and 1.4.3.** The entries of the determinant  $\begin{vmatrix} 2c(2^{l-1}) + v_2 \\ u_3 \end{vmatrix}$  used in

Step 1.4.3 can be represented with  $b + 1$  bits since  $2c(2^{l-1}) + v_2$  is either  $c(2^l)$  or  $c(2^l) + v_2$ . And the same holds for the entries of the determinant used at Step 1.4.3.

### 3.6 Second step: exponential reduction

The second major step of the algorithm, to be described in this subsection, either evaluates the sign of  $\kappa_3$  or finds a vector  $R' = R - \theta_1 U_1 - \theta_2 U_2$ ,  $\theta_1, \theta_2 \in \{-1, 0, 1\}$

Figure 5: Illustration of the selection of  $R'$ .

such that  $x_R, y_R$  are  $b$ -bit integers and  $|z_R| \leq \frac{z_3}{2}$ . In order to do that, we will further subdivide the box  $\mathcal{B}$  into four sub-boxes such that, for any  $r$  lying in each of those sub-boxes, either such a vector  $R'$  can be determined or the sign of  $\kappa_3$  can be readily obtained.

The projection of box  $\mathcal{B}$  onto the plane is the parallelogram  $u_1 \oplus u_2$ . The algorithm locates the projection  $r$  of  $R$  with respect to the two diagonals of the parallelogram joining  $u_1$  to  $u_2$  and  $O$  to  $u_1 + u_2$  by evaluating the sign of  $2 \times 2$  determinants

$$\begin{vmatrix} r & \\ u_1 + u_2 & \end{vmatrix} \text{ and } \begin{vmatrix} r - u_1 & \\ u_2 - u_1 & \end{vmatrix} \text{ (see Figure 5).}$$

We illustrate the step just for one of the four sub-boxes; handling of the other three cases is trivially analogous. Assume therefore, without loss of generality, that  $r$  belongs to triangle  $(O, u_1, \frac{u_1 + u_2}{2})$ . Then

- if  $z_R > \sup(z_1, \frac{z_1 + z_2}{2})$ , then  $\kappa_3 > 0$ ,
- if  $z_R < 0$ , then  $\kappa_3 < 0$ ,

- else, we choose  $R'$  as the vector among the two vectors  $R$  and  $R - U_1$  whose 3-rd component has the smaller modulus. It follows that

$$|z_{R'}| \leq \frac{\sup(z_1, z_2)}{2} \leq \frac{z_3}{2}.$$

### 3.7 Nonindependent vectors

We have assumed above that  $(u_1, u_2)$  are linearly independent vectors. If these vec-

tors are not independent, the minor  $\begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix}$  of  $D = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}$  associated to the  $z_3$  component of  $u_3$  vanishes and we can simply replace  $z_3$  by 0 without modifying the determinant:

$$D = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & 0 \end{vmatrix}.$$

### 3.8 Complexity analysis of the algorithm

At each iteration, either the algorithm evaluates the sign of  $\kappa_3$  and ends by the computation of a  $2 \times 2$  determinant, or iterates with a  $3 \times 3$  determinant where the greatest (in absolute value) element of the last column has been divided by at least two while the others remain unchanged. It follows that the number of iterations is at most  $3b$ .

Each iteration consists of Substeps 1.1-1.6 and Step 2. The cost of each step is dominated by evaluating signs of  $2 \times 2$  determinants with  $(b+1)$ -bit integer entries. Substep 1.1 requires three such evaluations, Substep 1.2 one, Substep 1.3 at most  $2b$ , Substep 1.4 at most  $2b$ , Substep 1.5 at most one, and Substep 2 at most two. Thanks to Theorem 1, we have the following theorem.

**Theorem 2** *Let  $D$  be a  $3 \times 3$  determinant with  $b$ -bit integer entries. There exists an algorithm that evaluates the sign of  $D$  using only  $(b+1)$ -bit arithmetic. The algorithm requires at most  $3b$  iterations, each iteration involving the evaluation of at most  $4b+9$  signs of  $2 \times 2$  determinants with  $(b+1)$ -bit integer entries. In the worst-case, the algorithm requires at most  $3b^2(4b+9)$  elementary steps, each elementary step involving  $O(1)$  additions/subtractions, comparisons and euclidean divisions.*

## 4 Geometric applications

Most geometric tests can be reduced to computing the sign of a determinant. This section shows such reductions for the most basic geometric tests.

### 4.1 `which_side`

Given  $d$  points  $A_1, \dots, A_d$  in  $d$ -space, and another point  $X$  of  $\mathbb{R}^d$ , Function `which_side` determines whether  $X$  belongs to the hyperplane  $H$  passing through the  $A_i$  or, otherwise, to which half space limited by  $H$ . This function is at the core of many geometric algorithms, and, in particular, of all algorithms computing convex hulls of points in  $\mathbb{R}^d$ .

Function `which_side` can be implemented as the evaluation of the sign of the  $d \times d$  determinant

$$D = \begin{vmatrix} A_1 - X \\ \vdots \\ A_d - X \end{vmatrix}$$

with  $(b + 1)$ -bit integer entries, if the points have  $b$ -bit integer coordinates.

### 4.2 `sign_dot_product`

Given two 2-vectors  $U_1 = (x_1, y_1)$  and  $U_2 = (x_2, y_2)$  with  $b$ -bit integer components, one can determine the sign of the dot product  $U_1 \cdot U_2$  by determining the sign of the  $2 \times 2$  determinant with  $b$ -bit integer entries

$$\begin{vmatrix} x_1 & y_1 \\ -y_2 & x_2 \end{vmatrix} = U_1 \cdot U_2.$$

Given two 3-vectors  $U_1 = (x_1, y_1, z_1)$  and  $U_2 = (x_2, y_2, z_2)$  with  $b$ -bit integer components, if  $x_1 \neq 0$ , one can determine the sign of the dot product  $U_1 \cdot U_2$  by determining the sign of the  $3 \times 3$  determinant with  $b$ -bit integer entries

$$\begin{vmatrix} y_1 & -x_1 & 0 \\ z_1 & 0 & -x_1 \\ x_2 & y_2 & z_2 \end{vmatrix} = x_1 U_1 \cdot U_2.$$

If  $x_1 = 0$ , the problem is reduced to the 2-dimensional case.

These results immediately apply for comparing the norms of two vectors. Indeed, given two vectors  $U_1$  and  $U_2$ ,

$$|U_1|^2 - |U_2|^2 = (U_1 + U_2) \cdot (U_1 - U_2).$$

It follows that comparing the norms of two  $d$ -vectors with  $b$ -bit integer components, is equivalent to evaluating the sign of a  $d \times d$  determinant with  $(b + 1)$ -bit integer entries.

### 4.3 in\_circle

The basic numerical test involved in the construction of Voronoi diagrams in the plane is the following. Given are three points  $A_i = (x_i, y_i)$ ,  $i = 1, 2, 3$ , and another point  $X = (x, y)$  with  $b$ -bit integer coordinates. The test consists in deciding whether  $X$  lies on the circle  $C$  passing through  $A_1$ ,  $A_2$  and  $A_3$ , inside  $C$  or outside  $C$ . This is equivalent to determining the sign of the following  $3 \times 3$  determinant

$$\begin{aligned} \text{in\_circle}(X) &= \begin{vmatrix} x_1 - x & x_2 - x & x_3 - x \\ y_1 - y & y_2 - y & y_3 - y \\ x_1^2 + y_1^2 - x^2 - y^2 & x_2^2 + y_2^2 - x^2 - y^2 & x_3^2 + y_3^2 - x^2 - y^2 \end{vmatrix} \\ &= \begin{vmatrix} x_1 - x & x_2 - x & x_3 - x \\ y_1 - y & y_2 - y & y_3 - y \\ 0 & (x_2 - x)(x_2 - x_1) + (y_2 - y)(y_2 - y_1) & (x_3 - x)(x_3 - x_1) + (y_3 - y)(y_3 - y_1) \end{vmatrix} \\ &= \frac{1}{x_1 - x} \begin{vmatrix} x_1 - x & x_2 - x & x_3 - x \\ 0 & (x_1 - x)(y_2 - y) - (x_2 - x)(y_1 - y) & (x_1 - x)(y_3 - y) - (x_3 - x)(y_1 - y) \\ 0 & (x_2 - x)(x_2 - x_1) + (y_2 - y)(y_2 - y_1) & (x_3 - x)(x_3 - x_1) + (y_3 - y)(y_3 - y_1) \end{vmatrix} \\ &= \begin{vmatrix} (x_1 - x)(y_2 - y) - (x_2 - x)(y_1 - y) & (x_1 - x)(y_3 - y) - (x_3 - x)(y_1 - y) \\ (x_2 - x)(x_2 - x_1) + (y_2 - y)(y_2 - y_1) & (x_3 - x)(x_3 - x_1) + (y_3 - y)(y_3 - y_1) \end{vmatrix} \end{aligned}$$

It follows that Function `in_circle` can be implemented as the evaluation of the sign of a  $2 \times 2$  determinant with  $(2b + 3)$ -bit integer entries.

A similar computation shows that the analogous Function `in_sphere` can be implemented as the evaluation of the sign of the following  $3 \times 3$  determinant with  $(2b + 4)$ -bit integer entries.

$$\text{in\_sphere}(X) = \frac{1}{x_1 - x} \begin{vmatrix} (x_1 - x)(y_2 - y) - (x_2 - x)(y_1 - y) & (x_1 - x)(y_3 - y) - (x_3 - x)(y_1 - y) & (x_1 - x)(y_4 - y) - (x_4 - x)(y_1 - y) \\ (x_1 - x)(z_2 - z) - (x_2 - x)(z_1 - z) & (x_1 - x)(z_3 - z) - (x_3 - x)(z_1 - z) & (x_1 - x)(z_4 - z) - (x_4 - x)(z_1 - z) \\ (x_2 - x)(x_2 - x_1) + (y_2 - y)(y_2 - y_1) + (z_2 - z)z_1 & (x_3 - x)(x_3 - x_1) + (y_3 - y)(y_3 - y_1) + (z_3 - z)z_1 & (x_4 - x)(x_4 - x_1) + (y_4 - y)(y_4 - y_1) + (z_4 - z)z_1 \end{vmatrix}.$$



#### 4.4 intersections\_sorting

When constructing arrangements of line segments in the plane and trapezoidal maps (e.g. by a sweep line algorithm), the following crucial numerical test is used. Let  $A_0A_1$ ,  $A_2A_3$ ,  $A_4A_5$  and  $A_6A_7$  be four line segments. The test consists in deciding if the  $x$ -coordinate  $x_I$  of the intersection point  $I$  of  $A_0A_1$  and  $A_2A_3$  is smaller or greater than the  $x$ -coordinate  $x_J$  of the intersection point  $J$  of  $A_4A_5$  and  $A_6A_7$ . If the coordinates of points  $A_i$  are  $b$ -bit integers, this test reduces to evaluating the sign of a  $2 \times 2$  determinant with  $(3b + 3)$ -bit integer entries.

Indeed, if  $A_i = (x_i, y_i)$  for  $i = 0, \dots, 7$ ,

$$x_I = \frac{A_I}{B_I}$$

where

$$A_I = \begin{vmatrix} x_1 - x_0 & x_0y_1 - x_1y_0 \\ x_3 - x_2 & x_2y_3 - x_3y_2 \end{vmatrix}$$

$$B_I = \begin{vmatrix} x_1 - x_0 & y_1 - y_0 \\ x_3 - x_2 & y_3 - y_2 \end{vmatrix},$$

and a similar expression can be found for  $x_J$ . Comparing  $x_I$  and  $x_J$  reduces to testing the sign of the  $2 \times 2$  determinant  $\begin{vmatrix} A_I & B_I \\ A_J & B_J \end{vmatrix}$  where each element  $A_I$  and  $A_J$  are  $(3b + 3)$ -bit integers while  $B_I$  and  $B_J$  are  $(2b + 3)$ -bit integers.

## 5 Experimental results

### 5.1 $2 \times 2$ determinants

The algorithm described in section 2 has been implemented in the C++ programming language. The integers are represented as double-precision floating point-variables since floating-point arithmetic allows to use 53-bit entries and is much faster than integer arithmetic on modern workstations. We report experimental results obtained on a SUN 4 sparc workstation (Sun 4C/75) using the C++ ATT compiler. Computing times have been obtained using the UNIX command `prof`.

The algorithm described in this paper, hereafter called the *exact algorithm*, is compared to the *direct algorithm* that uses floating-point arithmetic and evaluates the

algorithm	uniform distribution	null determinants
direct ( $\mu\text{s}$ )	2.99	3.24
exact ( $\mu\text{s}$ )	11.64	50.98
ratio	3.89	15.73

Table 1: Experimental results for  $2 \times 2$  determinants.

sign of  $D = \begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \end{vmatrix}$  by first computing the two products  $x_1y_2$  and  $x_2y_1$  and then testing whether  $x_1y_2 > x_2y_1$  ( $D > 0$ ),  $x_1y_2 < x_2y_1$  ( $D < 0$ ), or  $x_1y_2 = x_2y_1$  ( $D = 0$ ).

The two methods have been tested on two types of determinants :

- determinants with integer entries uniformly distributed in the range  $[-2^{53}, 2^{53}]$ .
- null determinants of the form  $\begin{vmatrix} a & a \\ b & b \end{vmatrix}$  with  $a$  and  $b$  uniformly distributed in the range  $[-2^{53}, 2^{53}]$  (i.e. points on the line  $y = x$ ).

Both procedures have also been incorporated in two standard algorithms for constructing the convex hull of a set of points in the plane.

The cost of the exact algorithm is strongly related to the number  $I$  of iterations which are performed. By Theorem 1,  $I$  is bounded in the worst-case by  $b$ , the number of bits used to represent the entries, but, in practice, it depends heavily on the entries. One can expect that uniformly distributed entries yields a smaller  $I$  than degenerate entries. This is confirmed by our experiments, summed up in Table 1.

The second column of Table 1 presents results averaged over 100 000 determinants whose entries are uniformly distributed in the range  $[-2^{53}, 2^{53}]$ . The average number of iterations in the exact algorithm is 1.5.

The third column of Table 1 presents results averaged over 100 000 determinants of the form  $\begin{vmatrix} a & a \\ b & b \end{vmatrix}$  where  $a$  and  $b$  are uniformly distributed in the range  $[-2^{53}, 2^{53}]$ .

The average number of iterations in the exact method is 10.7.

Both algorithms have also been incorporated in two well-known algorithms computing the convex hull of a set of points in the plane, namely Graham and Jarvis

	uniform distribution	null determinants
number of iterations	1.0013	22.5
number of $2 \times 2$ det.	20.8	416

Table 2: Experimental results for  $3 \times 3$  determinants.

algorithms [PS85]. All the decisions based on numerical computations can be replaced by evaluating signs of  $2 \times 2$  determinants whose entries are differences of two components of the points. It follows that, if  $b$ -bit arithmetic is used, the implementations using the exact algorithm for evaluating the signs of the determinants are provably robust as soon as the entries can be represented by  $(b - 1)$ -bit integers.

For both Graham and Jarvis algorithms, tests have been performed on points uniformly distributed in the square  $Q = [-2^{52}, 2^{52}] \times [-2^{52}, 2^{52}]$  and on the circle centered at the origin with radius  $2^{52}$ . If we use the exact method for evaluating the signs of the involved determinants instead of the direct floating point method, the overall computation is slowed down the by a factor ranging between 1.1 and 1.5.

## 5.2 $3 \times 3$ determinants

The method has also been implemented for  $3 \times 3$  determinants. We report machine independent results, namely the number of evaluations of signs of  $2 \times 2$  determinants and the number of iterations.

As in two dimensions, the algorithm has been tested on several types of determinants:

- determinants with entries uniformly distributed in  $[-2^{52}, 2^{52}]$ ,
- null determinants with entries in the plane  $x + y + z = 0$  with  $x$  and  $y$  coordinates uniformly distributed in  $[-2^{52}, 2^{52}]$ , The  $x$  and  $y$  coordinates are uniformly distributed in  $[-2^{52}, 2^{52}]$ .

Results are reported in Table 2.

## 6 Concluding remarks

We have presented an algorithm that evaluates signs of  $2 \times 2$  and  $3 \times 3$  determinants with  $b$ -bit integer entries using only  $b$  and  $(b + 1)$ -bit arithmetic respectively. We have also shown how this algorithm can be used in several basic tests in geometric computation. The algorithm has been implemented and compared with the direct floating-point implementation. Of course, this comparison is not quite fair since a floating-point implementation is not guaranteed to be always correct. Experimental results show that our algorithm has a good performance penalty.

An obvious direction for further research is to extend the present work to higher dimensions. The only difficulty there is to generalize Step 2 (Subsection 3.6) which reduces the last component by a constant factor while keeping the other components smaller than  $2^b$ . Such an extension would provide, at least in principle, an extremely general solution to robustness in geometric computation since, by a result of Valiant [Val79], any algebraic expression of size  $e$  can be constructively written as an  $(e + 2) \times (e + 2)$  determinant whose entries are either variables or constants.

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