Evaluating signs of determinants using single-precision arithmetic

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

INRIA

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

N˚ 2306

Juillet 1994

PROGRAMME 4

Robotique,

image

et vision

ISSN 0249-6399

Evaluating signs of determinants using single-precision arithmetic

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

Programme 4 — Robotique, image et vision

Projet Prisme

Rapport de recherche n ° 2306 — Juillet 1994 — 27 pages

Abstract: We propose a method to evaluate signs of 2×2 and 3×3 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)

Research of F. Avnaim, J-D. Boissonnat, O. Devillers and M. Yvinec was supported in part by ESPRIT Basic Research Action 7141 (ALCOMII). Work of F. Preparata was supported by NSF Grant CCR91-96176. Part of this work was done while J-D. Boissonnat was visiting Brown University.

*INRIA, BP93, 06902 Sophia-Antipolis cedex (France), E-mail: Francis.Avnaim@sophia.inria.fr
**INRIA, E-mail: Jean-Daniel.Boissonnat@sophia.inria.fr.
***INRIA, E-mail: Olivier.Devillers@sophia.inria.fr.
****Brown University, Department of Computer Science, Providence, RI 02912-1910 (USA) E-mail: franco@cs.brown.edu.
*****INRIA and CNRS, URA 1376, Laboratoire I3S, 250 Rue Albert Einstein, 06560 Valbonne (France), E-mail: Mariette.Yvinec@sophia.inria.fr.

Unité de recherche INRIA Sophia-Antipolis
2004 route des Lucioles, BP 93, 06902 SOPHIA-ANTIPOLIS Cedex (France)
Téléphone : (33) 93 65 77 77 – Télécopie : (33) 93 65 77 65

Evaluation du signe d'un déterminant en arithmétique simple précision

Résumé : Nous proposons une méthode d'évaluation du signe des déterminants 2×2 et 3×3 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 detailled analysis). Significant improvements over the naive method have been recently obtained. In particular, a promissing 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 $O(d^3 b)$ and uses $2b + 1.5d$ bits to represent the values. Our algorithm is quite different. It is limited to 2×2 and 3×3 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 2×2 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:

$$x_2 \;=\; x_1\, k_1 \,+\, x_r \;\text{ with }\; k_1 \in I\!N \text{ and } 0 \leq x_r < x_1$$

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:

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

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

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 2×2 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 3×3 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 $\kappa_1, \kappa_2, \kappa_3 \in I\!R$. 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 κ_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 κ_3 can be determined. We have:

$$\kappa_3 = z_3 - \kappa_1 z_1 - \kappa_2 z_2. \tag{3}$$

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 κ_3, but we can write:

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

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 $\mathbb{B}$ 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 $l_1, l_2 \in \mathbb{Z}$. $\mathbb{B}$ contains plane H and can be considered as an approximation of H.

The geometric interpretation of the above dicussion is now: if U_3 lies above (below) $\mathbb{B}$, κ_3 is positive (negative), and otherwise, U_3 can be replaced by a vector contained in $\mathcal{B}$.

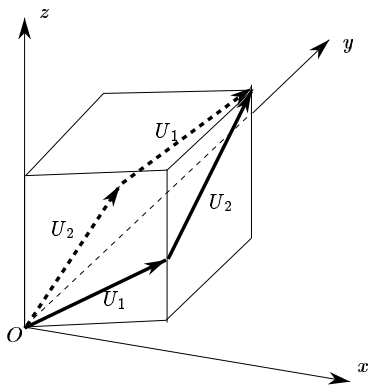

Figure 1: Box $\mathcal{B}$.

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 $\mathbb{B}$, above $\mathbb{B}$, or inside some box of $\mathbb{B}$. In the first two cases, D reduces to a 2×2 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 κ_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 2×2 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 κ_3 or, when U_3 lies in $\mathbb{B}$, 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

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

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 κ_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 2×2 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

$$c_u = c_v + \epsilon_1 u_1 + \epsilon_2 u_2. \tag{5}$$

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

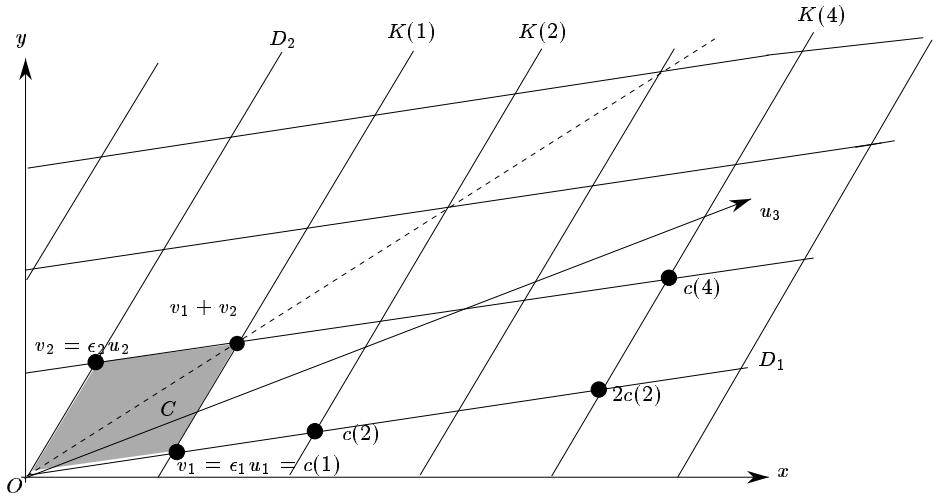

Figure 2: Illustration of Step 1.

u_3 is included in $\mathcal{C}'_0$, $k'_1 = k'_2 = 0$, 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 $K(2)$, $K(4)$, $K(8)$, ... Each of these probes may yield the sign of κ_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 2×2 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 2×2 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

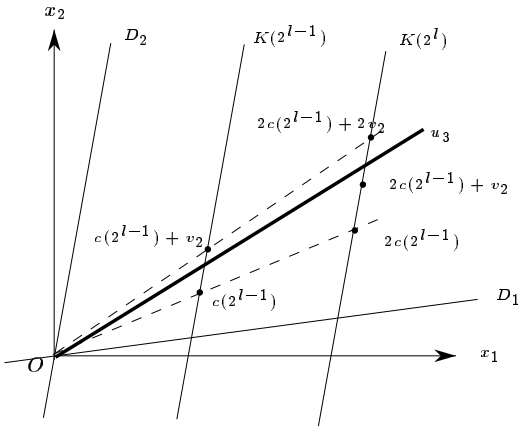

Figure 3: For Substep 1.3.3.

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 λ such that Ou_3 crosses $K(\lambda)$ but not $K(\lambda+1)$ and sets $\lambda_f = \lambda$. The determination of λ is a binary search. This search involves k steps numbered $k-1, k-2, \ldots, 0$. We denote λ_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 λ_{h+1} and $c(\lambda_{h+1})$. We now explain how λ_h and $c(\lambda_h)$ are inductively computed from λ_{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 2×2 determinant $\Delta' =$

$\begin{vmatrix} u_3 - c(\lambda_{h+1}) - c(2^h) \\ v_2 \end{vmatrix}$, 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 $\begin{vmatrix} u_3 \\ c(\lambda_{h+1}) + c(2^h) + v_2 \end{vmatrix}$.

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 $k-1, k-2, \ldots, 0$. 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 $\begin{vmatrix} u_3 - c(\lambda_f) - v_2 \\ v_1 \end{vmatrix} \geq 0$, 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 than 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 $|z_u| < 2^b$, $z_R = z_3 - z_u$ can be computed using $(b+1)$-bit arithmetic. If z_u is negative with $|z_u| > 2^b$, then z_R and κ_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 $\mathcal{SP}$ choosen 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

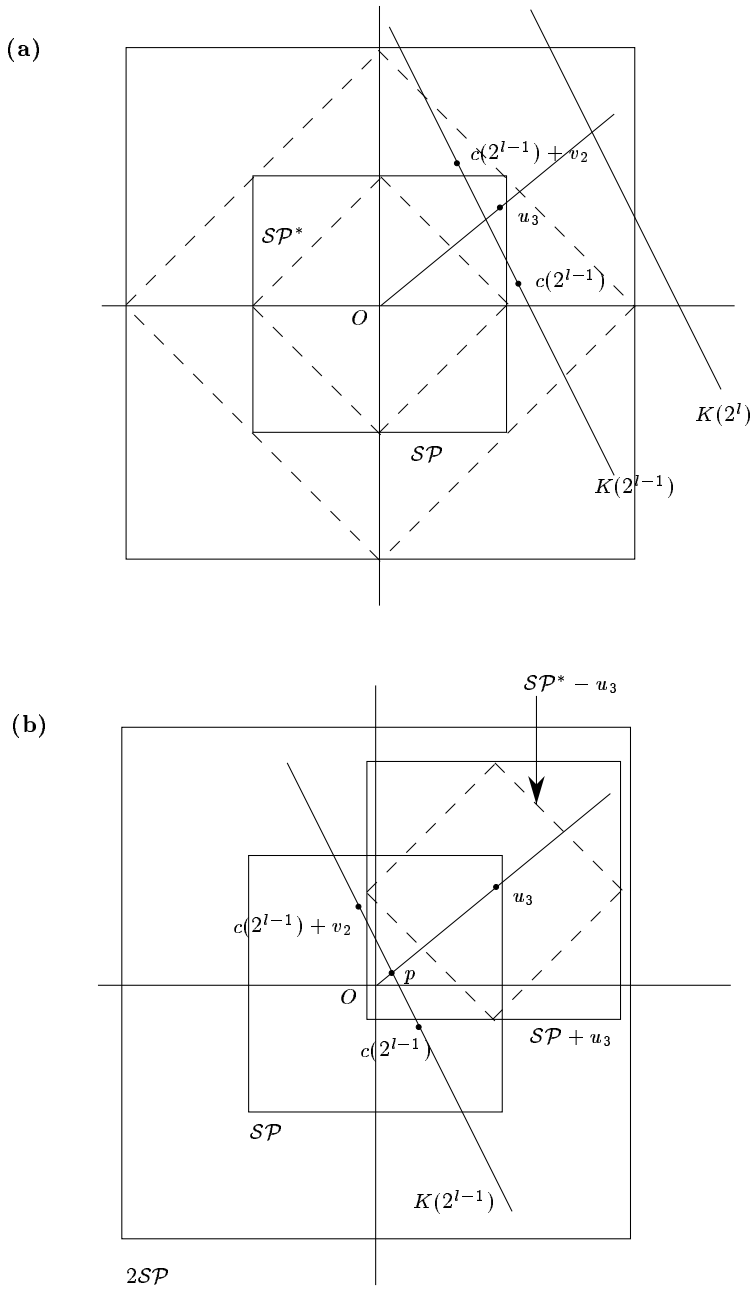

Figure 4: Illustrations for the cases : (a) $c(2^{l-1}) \notin \mathcal{SP}$ and $c(2^{l-1}) + v_2 \notin \mathcal{SP}$, (b) $c(2^{l-1}) - u_3 \notin \mathcal{SP}$ and $c(2^{l-1}) + v_2 - u_3 \notin \mathcal{SP}$.

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 κ_3 or finds a vector $R' = R - \theta_1 U_1 - \theta_2 U_2$, $\theta_1, \theta_2 \in \{-1, 0, 1\}$

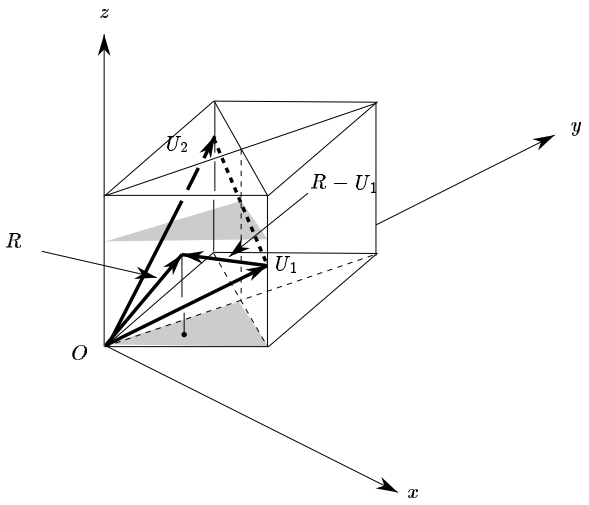

Figure 5: Illustration of the selection of R'.

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 κ_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 2×2 determinants $\begin{vmatrix} r \\ u_1 + u_2 \end{vmatrix}$ and $\begin{vmatrix} r - u_1 \\ u_2 - u_1 \end{vmatrix}$ (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 vectors 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 κ_3 and ends by the computation of a 2×2 determinant, or iterates with a 3×3 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 2×2 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 3×3 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 2×2 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 $A_1, \ldots, A_d$ 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 2×2 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 3×3 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 3×3 determinant

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

It follows that Function `in_circle` can be implemented as the evaluation of the sign of a 2×2 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 3×3 determinant with $(2b+4)$-bit integer entries.

$$\texttt{in\_sphere}(X) = \frac{1}{x_1 - x}$$

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

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 2×2 determinant with $(3b+3)$-bit integer entries.

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

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

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 2×2 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 2×2 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 worstation (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 (μs)	2.99	3.24
exact (μs)	11.64	50.98
ratio	3.89	15.73

Table 1: Experimental results for 2×2 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 2×2 det.	20.8	416

Table 2: Experimental results for 3×3 determinants.

algorithms [PS85]. All the decisions based on numerical computations can be replaced by evaluating signs of 2×2 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 3×3 determinants

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

Acknowledgments

Jean-Pierre Merlet is acknowledged for supplying to us his interactive drawing preparation system JPdraw .

References

[BJMM93] M. Benouamer, P. Jaillon, D. Michelucci, and J.-M. Moreau. A lazy solution to imprecision in computational geometry. In *Proc. 5th Canad. Conf. Comput. Geom.*, pages 73–78, Waterloo, Canada, 1993.

[Cla92] K. L. Clarkson. Safe and effective determinant evaluation. In *Proc. 33rd Annu. IEEE Sympos. Found. Comput. Sci.*, pages 387–395, 1992.

[FM91] S. Fortune and V. Milenkovic. Numerical stability of algorithms for line arrangements. In *Proc. 7th Annu. ACM Sympos. Comput. Geom.*, pages 334–341, 1991.

[For89] S. Fortune. Stable maintenance of point set triangulations in two dimensions. In *Proc. 30th Annu. IEEE Sympos. Found. Comput. Sci.*, pages 494–505, 1989.

[For92] S. Fortune. Numerical stability of algorithms for 2-d Delaunay triangulations and Voronoi diagrams. In *Proc. 8th Annu. ACM Sympos. Comput. Geom.*, pages 83–92, 1992.

[FV93] S. Fortune and C. J. Van Wyk. Efficient exact arithmetic for computational geometry. In *Proc. 9th Annu. ACM Sympos. Comput. Geom.*, pages 163–172, 1993.

[GSS89] L. J. Guibas, D. Salesin, and J. Stolfi. Epsilon geometry: building robust algorithms from imprecise computations. In *Proc. 5th Annu. ACM Sympos. Comput. Geom.*, pages 208–217, 1989.

[GY86] D. H. Greene and F. F. Yao. Finite-resolution computational geometry. In *Proc. 27th Annu. IEEE Sympos. Found. Comput. Sci.*, pages 143–152, 1986.

[HHK89] C. M. Hoffmann, J. E. Hopcroft, and M. T. Karasick. Robust set operations on polyhedral solids. *IEEE Comput. Graph. Appl.*, 9(6):50–59, November 1989.

[KLN91] M. Karasick, D. Lieber, and L. R. Nackman. Efficient Delaunay triangulations using rational arithmetic. *ACM Trans. Graph.*, 10:71–91, 1991.

[Mil88a] V. Milenkovic. *Verifiable Implementations of Geometric Algorithms using Finite Precision Arithmetic.* Phd thesis, Carnegie Mellon University, 1988.

[Mil88b] V. Milenkovic. Verifiable implementations of geometric algorithms using finite precision arithmetic. *Artificial Intelligence*, 37:377–401, 1988.

[Mil89] V. Milenkovic. Double precision geometry: a general technique for calculating line and segment intersections using rounded arithmetic. In *Proc. 30th Annu. IEEE Sympos. Found. Comput. Sci.*, pages 500–505, 1989.

[PS85] F. P. Preparata and M. I. Shamos. *Computational Geometry: an Introduction.* Springer-Verlag, New York, NY, 1985.

[SI88] K. Sugihara and M. Iri. Geometric algorithms in finite-precision arithmetic. Technical Report 88-10, Math. Eng. and Physics Dept., U. of Tokyo, Japan, September 1988.

[Val79] L. Valiant. Completeness classes in algebra. In *Proc. 11th Annu. ACM Sympos. Theory Comput.*, pages 249–261, 1979.

Unité de recherche INRIA Lorraine, Technopôle de Nancy-Brabois, Campus scientifique,
615 rue du Jardin Botanique, BP 101, 54600 VILLERS LÈS NANCY
Unité de recherche INRIA Rennes, Irisa, Campus universitaire de Beaulieu, 35042 RENNES Cedex
Unité de recherche INRIA Rhône-Alpes, 46 avenue Félix Viallet, 38031 GRENOBLE Cedex 1
Unité de recherche INRIA Rocquencourt, Domaine de Voluceau, Rocquencourt, BP 105, 78153 LE CHESNAY Cedex
Unité de recherche INRIA Sophia-Antipolis, 2004 route des Lucioles, BP 93, 06902 SOPHIA-ANTIPOLIS Cedex

Éditeur
INRIA, Domaine de Voluceau, Rocquencourt, BP 105, 78153 LE CHESNAY Cedex (France)
ISSN 0249-6399