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On computing Hilbert bases via the Elliot–MacMahon Algorithm

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Abstract

The ways of using the Elliot–MacMahon algorithm to compute the Hilbert base of a system of linear Diophantine equations known so far are either not efficient or can fail to terminate. We present a version of an algorithm exploiting this range of ideas, which however is reasonably efficient as well as finite.

Keywords: Linear Diophantine equations; Elliot-MacMahon algorithm; Hilbert basis

1. Introduction

The problem of computing the minimal generating set $H$ of the semigroup $\Sigma$ of the nonnegative integer solutions of the system of equations

$$Ax = 0,$$  \hspace{1cm} (1)

where $A$ is a $d \times n$ integer matrix, recently received a lot of attention, particularly in computer science (AC-unification, Petri nets), in integer linear programming, as well as in combinatorics and computational commutative algebra. We refer the reader to [1, 2, 6, 7, 10–14] for more details, references and applications. We will call $H$ the Hilbert base of $A$.

It was observed recently that a modification of the classical Elliot–MacMahon algorithm for computing the graded generating function of $\Sigma$ can be used to compute $H$. It works by repeated transformations of a set $S$ of certain subsets $S_i$ of vectors in $\mathbb{Z}_2^d$ in the following way. In each step a critical pair of vectors $\{x, y\}$ belonging to some $S_i \in S$ is chosen in such a way that the vector $A(x + y)$ is in certain sense “closer” to the origin than $Ax$ and $Ay$. Then $S_i$ is replaced by two sets $S_i \cup \{x + y\} - \{x\}$ and $S_i \cup \{x + y\} - \{y\}$. (Optionally, other $S_k \ni \{x, y\}$ are replaced simultaneously, as well.) The starting set $S$ consists of just one set, namely the set of standard basis vectors of $\mathbb{Z}_2^d$. Stanley [9] observed that when all $S_k \ni \{x, y\}$ are replaced simultaneously, the procedure can be interpreted as a sequence of subdivisions of a simplicial fan in $\mathbb{R}_2^n$.

Several obstacles lie on the way of making the procedure just described practically feasible. First, it is necessary to avoid computing the same element of $H$ repeatedly. This can be accomplished via the Stanley’s idea just mentioned. However, a naive way of using it might lead to an explosive exponential growth of the memory needed to store $S$. In Section 2 we will show
(see Proposition 2.1) that the simplicial fan $S$ can be recovered from its 1-skeleton, thus providing a crucial reduction in the memory usage.

Second, it is crucial to ensure a speedy termination of the procedure. Here the issue of the strategy to choose the critical pair $P = \{x, y\}$ needs to be addressed. Geometrically, it is natural to choose $P$ so that

$$x^T A^T A y < 0$$

(2)

holds. However, as Tomás [13] shows, the strategy of choosing $P$ on the basis of (2) alone can lead to failure of termination. The only strategy proved to be finite so far basically solves the equations of (1) one by one. This is well-known to be in general rather inefficient, as the size of the Hilbert base of these intermediate systems can be huge compared to the size of $H$ we seek. In Section 4 we will show that the strategy of selecting $P$ minimizing

$$\deg x + \deg y = \sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i$$

(3)

among $P$'s satisfying (2) is finite.

The remained of the paper is organized as follows. Section 2 concerns notation and preliminaries. The algorithm, for a range of strategies of choosing a critical pair, is described and shown to be complete in Section 3. Section 4 is devoted to a termination proof of our strategy, and Section 5 concludes the paper with a discussion and some data obtained from an experimental implementation of our algorithm.

2. Preliminaries

The notation used is mainly taken from Ziegler [15], Sturmfels [11] and Stanley [9].

2.1. Cones and fans

For a cone $C$, one can construct the complex $F(C)$ in the usual way, with the $i$-dimensional faces of $C$ corresponding to $(i - 1)$-dimensional simplices of $F(C)$. A cone $C$ is simplicial is $F(C)$ is a simplex. A simplicial cone $C \subseteq \mathbb{R}^n_{\geq 0}$ generated by linearly independent vectors $c_1, \ldots, c_k$ (notation $C = cone(c_1, \ldots, c_k)$) is called a lattice cone (or a unimodular cone) if any vector in $C \cap \mathbb{Z}^n$ can be expressed as a nonnegative integer linear combination of $c_1, \ldots, c_k$. The latter is equivalent to the existence of $n - k$ integer vectors $c_{k+1}, \ldots, c_n$ such that

$$\det(c_1^T, \ldots, c_n^T) = \pm 1.$$  

(4)

Geometrically, it means the absence of integer vectors in the interior of the parallelepiped defined by $0, c_1, \ldots, c_k$.

A fan $\mathcal{F}$ is a set of cones in $\mathbb{R}^k$ satisfying the following two properties.

(i) Every nonempty face $F$ of a cone $C \in \mathcal{F}$ also belongs to $\mathcal{F}$.

(ii) The intersection of two cones in $\mathcal{F}$ is a face of both of them.

A fan is called simplicial if all its cones are simplicial. A simplicial complex can be
naturally associated with a simplicial fan. Now we are going to define two operations which, given a simplicial fan \( \mathcal{F} \) in \( \mathbb{R}^n_{\geq 0} \), produce a new one.

\[ S_{xy}: \text{Edge split.} \text{ Given a cone } E = \text{cone}(x, y) \in \mathcal{F} \text{ replace each cone } C = \text{cone}(x, y, c_1, \ldots, c_k) \in \mathcal{F} \text{ by a pair of cones } C' = \text{cone}(x, x + y, c_1, \ldots, c_k), C'' = \text{cone}(y, x + y, c_1, \ldots, c_k). \]

\[ R_x : \text{Vertex removal. Given a ray } x \in \mathcal{F}, \text{ remove from } \mathcal{F} \text{ all the cones containing } x. \]

We shall consider fans obtained from \( \mathbb{R}^n_{\geq 0} \) by repeatedly applying edge splits and vertex removals. Formally, we define a family \( \Phi = \bigcup_{i \geq 0} \Phi_i \) of simplicial fans inductively by setting \( \Phi_0 = \{ \mathbb{R}^n_{\geq 0} \} \) and \( \Phi_{i+1} = S_{xy}(\Phi_i) \) for some cone \((x, y) \in \mathcal{F}_i \) or \( \Phi_{i+1} = R_x(\Phi_i) \) for some cone \((x) \in \mathcal{F}_i \).

Denote by \( G = G(\mathcal{F}) \) the 1-skeleton of the simplicial complex of \( \mathcal{F} \in \Phi \). As usual, \( V(G) \) and \( E(G) \) denote the sets of vertices and edges of \( G \), respectively.

**Proposition 2.1.** The cliques of \( G = G(\mathcal{F}) \) are in the natural one-to-one correspondence with the cones of \( \mathcal{F} \in \Phi \).

**Remark 1.** It is essential that \( \mathcal{F} \in \Phi \). For instance for a fan \( \mathcal{F} \) with the maximal cones \( \text{cone}(a, b) \), \( \text{cone}(a, c) \) and \( \text{cone}(b, c) \), where \( a = (1 \ 0 \ 0) \), \( b = (0 \ 1 \ 0) \) and \( c = (0 \ 0 \ 1) \), the clique \{a, b, c\} of \( G(\mathcal{F}) \) does not correspond to any cone of \( \mathcal{F} \).

**Proof.** We proceed by induction. Observe that the statement holds for the fan \( \{ \mathbb{R}^n_{\geq 0} \} \) and assume that it holds for \( \mathcal{F}_0 \in \Phi \).

Trivially, a cone \( C \in \mathcal{F}_0 \) corresponds to a clique \( G(C) \) of \( G_0 = G(\mathcal{F}_0) \). Hence, in particular, the proposition holds for \( \mathcal{F} = R_x(\mathcal{F}_0) \). Next, let \( \mathcal{F} = S_{xy}(\mathcal{F}_0) \). Observe that the graph \( G \) is obtained from the graph \( G_0 \) by replacing the edge \((x, y)\) with the two-path \((x, w, y)\), where \( w = x + y \), and joining \( w \) to the common neighbours of \( x \) and \( y \) in \( G_0 \). Clearly, it suffices to prove the statement for the maximal cliques only. Let \( C \) be a maximal clique in \( G \). If \( w \in C \) then \( C \) is a clique in \( G_0 \) unaffected by \( S_{xy} \). Thus \( \text{cone}(C) \) is a cone in \( \mathcal{F} \cap \mathcal{F}_0 \), and we are done. Now assume \( w \in C \). Observe that \( C - \{w\} \) is a clique of \( G_0 \) consisting of some of the common neighbours of \( x \) and \( y \) in \( G_0 \), as well as of either \( x \) or \( y \). (The latter follows from the maximality of \( C \).) Without loss of generality, \( x \in C \). Moreover, \( C_0 = C \cup \{y\} - \{w\} \) is a clique of \( G_0 \). Hence, by induction, \( \text{cone}(C_0) = \text{cone}(C - \{w\}, y) \) is a cone of \( \mathcal{F}_0 \) and \( \text{cone}(C) \in \mathcal{F} \) by definition of \( S_{xy} \).

**Remark 2.** Tomás observed, after a preliminary version of this paper was distributed, that a rather similar idea appears in [4]. The exposition we give here is however quite different from the one in [4] and is easily accessible for a reader unfamiliar with “constraint propagation” technique of [4].

The proposition just proved shows that the combinatorics of \( \mathcal{F} \in \Phi \) is completely encoded in \( G(\mathcal{F}) \). The following proposition, derived from Stanley [9, Lemma 3.7], deals with
the geometry of $\mathcal{F}$.

**Proposition 2.2** (Stanley [9]). *The cones of $\mathcal{F} \subseteq \Phi$ are lattice cones.*

**Proof** (Stanley [9]): For the fan $\{\mathbb{R}_{\geq 2}^n\}$ the statement holds. Assume that is holds for $\mathcal{F}_0 \in \Phi$. Then it clearly holds for $\mathcal{F} = R_\ell(\mathcal{F}_0)$. Let $\mathcal{F} = S_{xy}(\mathcal{F}_0)$ and $w = x + y \in C \subseteq \mathcal{F}$, with $C$ maximal (obviously it suffices to prove the statement for the maximal cones). Thus we can assume $x \in C$ and $C = \text{cone}(w, x_1, c_1, \ldots, c_k)$. Then $C_0 = \text{cone}(x, y, c_1, \ldots, c_k) \in \mathcal{F}_0$ by definition of $S_{xy}$ and is a lattice cone by assumption. Thus,

$$\begin{align*}
\pm 1 &= \det(c_1^T, y^T, c_1^T \ldots c_k^T, d_1^T \ldots d_{n-k-2}^T) \\
&= \det((x + y)^T, y^T, c_1^T \ldots c_k^T, d_1^T \ldots d_{n-k-2}^T),
\end{align*}$$

applying (4) to get the first equality, and a well-known determinantal identity to get the second one. Hence the proposition. $\square$

2.2. **Matrices and vectors**

The vectors $v \in \mathbb{Z}^n_{\geq 0}$ satisfying (1) form the semigroup $\Sigma$. The Hilbert base of $A$ is the (unique, cf. e.g. [8, Theorem 14.6]) set $H$ of vectors $v \in \mathbb{Z}^n_{\geq 0}$ satisfying (1) and such that

1. $x = \sum_{h \in H} a_h h$, $a_h \in \mathbb{Z}_{\geq 0}$ for any $x \in \Sigma$ (i.e. $H$ generates $\Sigma$);
2. $u - v \in \mathbb{Z}^n_{\geq 0}$ for any $u, v \in H$ (i.e. $H$ is minimal).

In what follows $\|x\|$ stands for the Euclidean norm of $x \in \mathbb{R}^n$ (i.e. $\|x\| = \sqrt{\sum_{i=1}^n x_i^2}$). The support of $x$ is the set $\text{supp } x = \{j \mid 1 \leq j \leq n, x_j \neq 0\}$.

3. **Description of the algorithm**

In this section we describe an algorithm $\text{HB} = \text{HB}(A, R, b, R', b')$ computing the intersection $H \cap P$ of the Hilbert base $H$ of $A$ with the set

$$P = \{x \in \mathbb{R}^n_{\geq 0} \mid Rx \leq b, R'x \leq b'\}, \quad R^{(i)} = (r_{ij}), \quad r_{ij} \geq 0.$$ 

We allow $R = R' = 0$, so that $H \cap P = H$ in this particular case.

$\text{HB}$ works by updating a fan $\mathcal{F}$ by applying edge splits (and, optionally, vertex removals) starting from $\mathcal{F} = \{\mathbb{R}_{\geq 2}^n\}$, $\mathcal{F}$ is stored as $G = G(\mathcal{F})$, as Proposition 2.1 allows. As $x \in V(G)$ satisfying (1) appear, they are stored in $H$, which is initially empty. We shall denote

$$E_S = E_S(G) = \{(x, y) \in E(G) \mid x^T A^T A y < 0, \quad R(x + y) \leq b, \quad R'(x + y) < b', \quad \text{there is no } w \in H \text{ with } x + y \geq w\}. \quad (5)$$
The edges \((x, y)\) for the splitting \(S_{xy}\) will always be selected from \(E_S\). The set \(E_S\) is maintained by calling \(HB\) recursively. This allows to describe the procedure in a greater generality. Other possibilities for maintaining \(E_S\) are described in Section 5.

The algorithm in pseudo-code is given in Fig. 1. First, we assume that the step (Optional) is not performed at all.

**Lemma 3.1.** Let \(w \in \mathcal{H} \cap \mathcal{P}\) lie in the interior of a cone \(C \in \mathcal{F}\), where \(G = \mathcal{G}(\mathcal{F})\) is obtained at some stage of the execution of the algorithm (assuming (Optional) not being performed). Then \(E_S = E_S(G) \neq \emptyset\).

**Proof.** As \(C = \text{cone}(c_1, \ldots, c_k)\) is a lattice cone (cf. Proposition 2.2) and \(w\) is in its interior,

\[
    w = \sum_{i=1}^{k} a_ic_i \quad \text{with} \quad a_i \geq 1 \quad \text{for} \quad 1 \leq i \leq k.
\]

Applying \(A\) to both sides of this expression yields

\[
    0 = \sum_{i=1}^{k} a_iAc_i.
\]

The latter implies that \(c_i^T A^TYc_j < 0\) for some \(1 \leq i \leq j \leq k\). As \(a_i \geq 1, a_j \geq 1\), and \(w \in P\), we have \(c_i + c_j \in P\). Hence \((c_i, c_j) \in E_S = \emptyset\). □

The following can be proved by a straightforward inspection of the definition of \(E_S\).

**Lemma 3.2.** Let \((x, y, v)\) be a triangle in \(G\) with \((x, v)\) and \((y, v)\) not in \(E_S\). Then \((x + y, v)\), should it arise during the run of algorithm, cannot belong to \(E_S\).

Thus the vertices of \(G\) removed during the step (Optional) are “redundant”, as they do not participate in updating of \(E_S\). Hence this step does not affect the outcome of the algorithm.

By Lemma 3.1, if the algorithm terminates then \(w \in \mathcal{H}\) will appear in the block Choice of the algorithm as \(w = x + y\) for some \((x, y) \in E_S\). Thus \(H\) will be returned upon termination.

4. **Termination**

The way the algorithm is described in Section 3 leaves the question of choosing \(w\) in the step Choice widely open. In fact, it is shown in [13] that for certain ways of performing this step, in particular when \((x, y)\) with the least value of \(x^T A^TYy\) is selected in \(E_S\), can lead to failure of termination. However, if we process \(V(G)\) degree by degree (recall that \(\text{deg} x = \sum_i x_i\)) then, as we shall show, the situation is quite satisfactory. We use a generalization of the technique due to Contejean and Devie [2, Section 5]. Namely, we prove the following.

**Theorem 4.1.** If \((x, y) \in E_S\) of minimal \(\text{deg} x + \text{deg} y\) is always selected at the step Choice, then the algorithm terminates.
Proof. Assume the contrary. Then in the graph $G$ we will have an infinite degree-increasing path $v_1, v_2, v_3, \ldots, v_i, \ldots$, where $v_{i+1} = v_i + x_i$ for some $x_i \in V(G)$ with $v_i^T A^T A x_i < 0$ for every $i \geq 1$. □

We shall use following generalization of [2, Lemma 5.1].

Claim 4.2.

\[ \lim_{k \to \infty} \frac{|A v_k|}{\deg v_k} = 0. \]

Proof of the Claim. It suffices to show that for any vertex $v_k \in V(G)$ we have $|A v_k|^2 \leq C \deg v_k$, for a constant $C$. We proceed by induction. Using $v_k^T A^T A x_k < 0$ we derive

\[ |A v_k|^2 = |A v_{k-1}|^2 + |A x_{k-1}|^2 + 2 v_k^T A^T A x_{k-1} \leq C \deg v_{k-1} + C \deg x_{k-1} = C \deg v_k. \]

Now define $u_k = v_k / \deg v_k$. Then $\deg u_k = 1$ and $\lim_{k \to \infty} |A u_k| = 0$. 1 As $u_k$ is a sequence on the $n$-dimensional simplex, which is a compact set, there is an adherence point $\ell$. Namely, $\ell$ is the limit of the subsequence $(u_{\phi(k)})_{k \geq 1}$, where $\phi$ is an increasing mapping on $\mathbb{Z}_{>0}$. By the continuity of the mapping $x \mapsto |A x|$, we have $|A \ell| = \lim_{k \to \infty} |A u_{\phi(k)}| = 0$.

Thus $\ell$ satisfies (1).

Starting from $\ell$, we construct a nonzero solution $r \in \mathbb{Z}_{>0}^n$ to (1) with $\text{supp } r \subset \text{supp } \ell$. Note that $\ell$ lies in the rational cone $\{ x \in \mathbb{R}_{>0}^n | A x = 0 \}$ (rational means that the extremal rays of it are rational vectors). As it is finite-dimensional, these rays can be given by vectors $r_i$'s in $\mathbb{Z}_{>0}^n$. Thus $\ell$ is a sum of $r_i$'s with nonnegative coefficients. Hence there is a constant $N$ such that $N \ell \geq r$, for some $r = r_i$, an extremal ray of the cone.

From the definition of $u_k$ we know that for $j \in \text{supp } \ell$, the $j$th entry of $v_k$ increases without bound as $k$ increases. Thus for some $k_0$ we have $v_{k_0} \geq r$, the desired contradiction. □

1 At this point it suffices to refer the reader to Contejean and Devie [2, Proposition 5.3] to complete the proof. As the second part of their proof (starting from the middle of p. 153) can be considerably streamlined, we would nevertheless like to give a complete proof here.
5. Discussion

5.1. The implementation

The author has done an experimental C language implementation of the algorithm described in Section 3, Fig. 1, with the minimal degree edges \((x, y)\) chosen at the step **Choice**, as justified by Theorem 4.1. The graph \(G\) is maintained using balanced binary trees to represent \(V(G)\) and the adjacencies of the vertices.

The recursive call to \(HB\) in **Choice** in the implementation is replaced by a search in the set \(H\) kept as an hierarchical structure. Due to the order of the edges in \(E_S\) processed, \(H\) always contains the elements of the Hilbert base of \(A\) of degree less than the one currently processed. While this works well when \(|H|\) is small, this becomes the bottleneck of algorithm when, roughly speaking, \(|H|\) becomes comparable with \(|V(G)|\). The alternatives would be to try the recursive call to \(HB\), or to some other algorithm computing the Hilbert base, e.g. the one described in [2]. Perhaps the most promising is to try to keep some vertices of \(G\) (removed by the step (Optional) in the current implementation), so that the recursive calls to \(HB\) would not have to rebuild (parts of) \(G\). This needs further analysis.

Also, one could try to keep \(H\) in the data structures known in computational geometry such as **Kd-trees** and **range trees**. For them, however, the worst case analysis does not give too much ground for optimism, either (the “rectangular query range” cannot be searched faster than \(O(\log^{n-1} |H|)\)). See [3] for details on this.

Finally, we observed that for large \(G\)’s the search of vertices in \(V(G)\) and the vertex adjacencies slowed down. More experiments are needed here with efficient ways of maintaining large sets.

5.2. Comparison and conclusion

It appears that the most efficient algorithm known to date is described in [2]. The major attraction of it is that the space needed by it is just a constant \(O(dn)\). However, it generally needs to perform more additions of vectors of length \(d\), i.e. linear combinations of columns of \(A\), than Elliott–MacMahon algorithm. For instance for the \((1 \times 2)\)-matrix \(A = (a, b)\) it needs to perform roughly \(ab\) vector additions, while Elliott–MacMahon takes at most \(\max\{|a|, |b|\}\).

The preliminary results of testing of the implementation appear to be encouraging. For instance, on the (proposed in [11, Chapter 6]) benchmarks **homogeneous primitive partition identities**, where \(A\) is the \((2 \times 2n)\)-matrix

\[
A = A_n = \left\{ \pm \begin{pmatrix} i \\ 1 \end{pmatrix} \mid 1 \leq i \leq n \right\},
\]

our program outperforms the program implementing [2], as much as by a factor of 100 for \(n \geq 6\). As well, on some tests from Tables II and III of [2] our program is faster (while on some, especially “small” ones, slower).
The memory problems start to affect the performance when \( G \) gets large. This is certainly the price one pays for the faster performance, not so uncommon in the theory of algorithms.

Finally, we must stress that there is apparently no particular algorithm for finding the Hilbert base which is much better than the rest of them. Specific domains need specific algorithms. We hope that Elliott–MacMahon algorithm will have its place, as well.

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References


List of Figures

Fig. 1 The algorithm $\mathbf{HB}(A, R, b, R', b')$. 
Input: 1. $A - d \times n$ integer matrix 
2. $R - r \times n$ matrix of nonnegative integers 
3. $b$ - vector in $\mathbb{R}_{\geq 0}^n$. 
4. $R' - r' \times n$ matrix of nonnegative integers 
5. $b'$ - vector in $\mathbb{R}_{\geq 0}^n$. 
Output: $\{x \in H \mid Rx \leq b, R'x < b'\}$, where $H$ is the Hilbert base of $A$

Initialize: $G := G(\mathbb{R}_{\geq 0}^n)$; $H := \emptyset$; 
for $v \in V(G)$ do 
  if $Rv \not< b$ or $R'v \not< b'$ then $G := R_v(G)$; fi; 
  if $Av = 0$ then $G := R_v(G)$, $H := H \cup \{v\}$; fi; 
od 
Set $E_S$ using (5); 

Main loop: while $E_S \neq \emptyset$ do
Choice: Choose $(x, y) \in E_S$

$$w := x + y, \quad H_w := \text{HB} \left( A, R, b, \begin{pmatrix} R' \\ I \end{pmatrix}, \begin{pmatrix} b' \\ w \end{pmatrix} \right);$$

if $H_w = \emptyset$ then
  if $Av = 0$ then $H := H \cup \{w\}$; $E_S := E_S - \{(x, y)\}$; 
  else $G := S_{xy}(G)$;
    $E_S := E_S \cup \{(w, u) \in E(G) \mid w^T A^T Au < 0, R(w + u) \leq b, R'(w + u) < b'\}$
  fi;
else $E_S := E_S - \{(x, y)\}$;
fi;

(Optional): for $v \in V(G)$ do
  if $\{u \mid (u, v) \in E_S\} = \emptyset$ then $G := R_v(G)$; fi 
od;
end;

return $H$;
END HB;

Fig. 1