A SHARP UPPER BOUND FOR THE LATTICE PROGRAMMING GAP

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Abstract. Given a full-dimensional lattice $\Lambda \subset \mathbb{Z}^d$ and a vector $\boldsymbol{l} \in \mathbb{Q}^d_{>0}$, we consider the family of the lattice problems

$$\text{Minimize}\,\{\boldsymbol{l}\cdot\boldsymbol{x} : \boldsymbol{x} \equiv \boldsymbol{r}(\bmod \Lambda), \boldsymbol{x} \in \mathbb{Z}^d_{\geq 0}\}\,, \quad \boldsymbol{r} \in \mathbb{Z}^d. \tag{0.1}$$

The *lattice programming gap* $\mathrm{gap}(\Lambda, \boldsymbol{l})$ is the largest value of the minima in (0.1) as $\boldsymbol{r}$ varies over $\mathbb{Z}^d$. We obtain a sharp upper bound for $\mathrm{gap}(\Lambda, \boldsymbol{l})$.

1. Introduction and statement of results

For linearly independent $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_k$ in $\mathbb{R}^d$, the set $\Lambda = \{\sum_{i=1}^k x_i \boldsymbol{b}_i,\, x_i \in \mathbb{Z}\}$ is a k-dimensional *lattice* with *basis* $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_k$ and *determinant* $\det(\Lambda) = (\det[\boldsymbol{b}_i \cdot \boldsymbol{b}_j]_{1\leq i,j\leq k})^{1/2}$, where $\boldsymbol{b}_i \cdot \boldsymbol{b}_j$ is the standard inner product of the basis vectors $\boldsymbol{b}_i$ and $\boldsymbol{b}_j$. The points $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^d$ are *equivalent modulo* Λ, denoted as $\boldsymbol{x} \equiv \boldsymbol{y}(\bmod \Lambda)$, if the difference $\boldsymbol{x} - \boldsymbol{y}$ is a point of Λ.

For a positive rational vector $\boldsymbol{l} \in \mathbb{Q}^d_{>0}$, a d-dimensional integer lattice $\Lambda \subset \mathbb{Z}^d$ and an integer vector $\boldsymbol{r} \in \mathbb{Z}^d$ we consider the lattice problem

$$\text{Minimize}\,\{\boldsymbol{l}\cdot\boldsymbol{x} : \boldsymbol{x} \equiv \boldsymbol{r}(\bmod \Lambda), \boldsymbol{x} \in \mathbb{Z}^d_{\geq 0}\}\,. \tag{1.1}$$

Let $m(\Lambda, \boldsymbol{l}, \boldsymbol{r})$ denote the value of the minimum in (1.1). We are interested in the *lattice programming gap* $\mathrm{gap}(\Lambda, \boldsymbol{l})$ of (1.1) defined as

$$\mathrm{gap}(\Lambda, \boldsymbol{l}) = \max_{\boldsymbol{r}\in\mathbb{Z}^d} m(\Lambda, \boldsymbol{l}, \boldsymbol{r})\,. \tag{1.2}$$

The lattice programming gaps were introduced and studied for sublattices of all dimensions in $\mathbb{Z}^d$ by Hoşten and Sturmfels [14]. Computing $\mathrm{gap}(\Lambda, \boldsymbol{l})$ is known to be NP-hard when d is a part of input (see [1]). For fixed d the value of $\mathrm{gap}(\Lambda, \boldsymbol{l})$ can be computed in polynomial time (see Section 3 in [14], [10] and [9]).

The lower and upper bounds for $\mathrm{gap}(\Lambda, \boldsymbol{l})$ in terms of the parameters $\Lambda, \boldsymbol{l}$ were given in [1]. The lower bound is known to be sharp. In this paper we improve on the upper bound and show that the obtained bound is attained for parameters $\Lambda, \boldsymbol{l}$ that satisfy certain arithmetic properties.

Date: January 21, 2017.

Let $|\cdot|$ denote the Euclidean norm and let γ_d be the d-dimensional Hermite constant (see e.g. Section IX.7 in [7]). In [1] it was shown that for any $\boldsymbol{l} \in \mathbb{Q}^d_{>0}$, $d \geq 2$, and any d-dimensional lattice $\Lambda \subset \mathbb{Z}^d$

$$\operatorname{gap}(\Lambda, \boldsymbol{l}) \leq \frac{d\gamma_d^{d/2} \det(\Lambda)(\sum_{i=1}^d l_i + |\boldsymbol{l}|)}{2} - \sum_{i=1}^{d} l_i \,. \tag{1.3}$$

The bound (1.3) was obtained using a geometric argument based on estimating the covering radius of a simplex, associated with the vector $\boldsymbol{l}$, via the covering radius of the unit d-dimensional ball. Note that by a result of Blichfeldt (see e.g. §38 in Chapter 6 of [13]) $\gamma_d \leq 2\left(\frac{d+2}{\sigma_d}\right)^{2/d}$, where σ_d is the volume of the unit d-ball; thus $\gamma_d = O(d)$. It follows from results in [2, Section 6] that the order $\operatorname{gap}(\Lambda, \boldsymbol{l}) = O_{d,\boldsymbol{l}}(\det(\Lambda))$, where the constant depends on d and $\boldsymbol{l}$, cannot be improved.

Let $\|\cdot\|_\infty$ denote the maximum norm. In this paper we use coverings that are based on the arithmetic properties of the integer lattices and improve the bound (1.3) as follows.

Theorem 1.1. *For any $\boldsymbol{l} \in \mathbb{Q}^d_{>0}$, $d \geq 2$, and any d-dimensional lattice $\Lambda \subset \mathbb{Z}^d$*

$$\operatorname{gap}(\Lambda, \boldsymbol{l}) \leq (\det(\Lambda) - 1)\|\boldsymbol{l}\|_\infty. \tag{1.4}$$

Using a link between the lattice programming gaps and the Frobenius numbers we also show that the bound (1.4) is sharp.

Theorem 1.2. *For $d \geq 2$ and any positive integer D there exist $\boldsymbol{l} \in \mathbb{Z}^d_{>0}$ and a lattice $\Lambda \subset \mathbb{Z}^d$ of determinant $\det(\Lambda) = D$ such that*

$$\operatorname{gap}(\Lambda, \boldsymbol{l}) = (D-1)\|\boldsymbol{l}\|_\infty. \tag{1.5}$$

2. Coverings of $\mathbb{R}^d$ and lattice programming gaps

Recall that the *Minkowski sum* $X + Y$ of the sets $X, Y \subset \mathbb{R}^d$ consists of all points $\boldsymbol{x} + \boldsymbol{y}$ with $\boldsymbol{x} \in X$ and $\boldsymbol{y} \in Y$. For a set $K \subset \mathbb{R}^d$ and a lattice $\Lambda \subset \mathbb{R}^d$, the Minkowski sum $K + \Lambda$ is a *packing* if the translates of K are mutually disjoint, a *covering* if $\mathbb{R}^d = K + \Lambda$ and a *tiling* if it is both packing and covering, simultaneously.

Let Λ be a lattice in $\mathbb{R}^d$ with basis $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d$. Let Λ_i denote the lattice generated by the first i basis vectors $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_i$ and let $\pi_i : \mathbb{R}^d \to \operatorname{span}_{\mathbb{R}}(\Lambda_{i-1})^\perp$ be the orthogonal projection onto the subspace $\operatorname{span}_{\mathbb{R}}(\Lambda_{i-1})^\perp$ orthogonal to $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_{i-1}$.

The vectors $\hat{\boldsymbol{b}}_i = \pi_i(\boldsymbol{b}_i)$ can be obtained using the Gram-Schmidt orthogonalisation of $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d$:

$$\begin{aligned} &\hat{\boldsymbol{b}}_1 = \boldsymbol{b}_1 \,, \\ &\hat{\boldsymbol{b}}_i = \boldsymbol{b}_i - \textstyle\sum_{j=1}^{i-1} \mu_{i,j} \hat{\boldsymbol{b}}_j \,, \;\; j = 2, \ldots, d \,, \end{aligned}$$

where $\mu_{i,j} = (\boldsymbol{b}_i \cdot \hat{\boldsymbol{b}}_j)/|\hat{\boldsymbol{b}}_j|^2$.

Define the box $B = B(\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d)$ as

$$B = [0, \hat{\boldsymbol{b}}_1) \times \cdots \times [0, \hat{\boldsymbol{b}}_d) \,.$$

We will need the following well-known and useful observation.

Lemma 2.1. *$B + \Lambda$ is a tiling of $\mathbb{R}^d$.*

Tilings of $\mathbb{R}^d$ with lattice translates of B were implicitly used already in the classical Babai's nearest lattice point algorithm (see [3] and Theorem 5.3.26 in [11]) and in the work of Lagarias, Lenstra and Schorr on Korkin-Zolotarev bases (see the proof of Theorem 2.6 in [16]). Lemma 2.1 was also explicitly stated (with translated B) by Cai and Nerurkar (see [6], Lemma 2). A proof of this result can be obtained by modifying the proof of Theorem 5.3.26 in [11]. We also remark that for the purposes of this paper we only need the coverings of $\mathbb{R}^d$ by the lattice translates of the closure of B.

In what follows, $\mathcal{K}^d$ will denote the space of all d-dimensional *convex bodies*, i.e., closed bounded convex sets with non-empty interior in the d-dimensional Euclidean space $\mathbb{R}^d$. Let also $\mathcal{L}^d$ denote the set of all d-dimensional lattices in $\mathbb{R}^d$. For $K \in \mathcal{K}^d$ and $\Lambda \in \mathcal{L}^d$ the *covering radius* of K with respect to Λ is the smallest positive number ρ such that any point $\boldsymbol{x} \in \mathbb{R}^d$ is covered by $\rho\, K + \Lambda$, that is

$$\rho(K, \Lambda) = \min\{\rho > 0 : \mathbb{R}^d = \rho K + \Lambda\} \,.$$

For further information on covering radii in the context of the geometry of numbers see e.g. Gruber [12] and Gruber and Lekkerkerker [13].

Given $\boldsymbol{l} \in \mathbb{Q}^d_{>0}$, consider the simplex $\Delta_{\boldsymbol{l}} = \left\{\boldsymbol{x} \in \mathbb{R}^d_{\geq 0} : \boldsymbol{l} \cdot \boldsymbol{x} \leq 1\right\}$. As it was shown in [1], the lattice programming gap can be expressed via the covering radius of $\Delta_{\boldsymbol{l}}$ with respect to Λ:

$$\mathrm{gap}(\Lambda, \boldsymbol{l}) = \rho(\Delta_{\boldsymbol{l}}, \Lambda) - \sum_{i=1}^{d} l_i \,. \tag{2.1}$$

3. Proof of Theorem 1.1

We will obtain an upper bound for $\mathrm{gap}(\Lambda, \boldsymbol{l})$ in terms of $\boldsymbol{l}$ and certain parameters of the lattice Λ that will imply (1.4).

By Theorem I (A) and Corollary 1 in Chapter I of Cassels [7], there exists a basis $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d$ of the lattice Λ of the form

$$\begin{aligned} \boldsymbol{b}_1 &= v_{11}\boldsymbol{e}_1 \,, \\ \boldsymbol{b}_2 &= v_{21}\boldsymbol{e}_1 + v_{22}\boldsymbol{e}_2 \,, \\ &\vdots \\ \boldsymbol{b}_d &= v_{d1}\boldsymbol{e}_1 + \cdots + v_{dd}\boldsymbol{e}_d \,, \end{aligned} \tag{3.1}$$

where $\boldsymbol{e}_i$ are the standard basis vectors of $\mathbb{Z}^d$, the coefficients v_{ij} are integers, $v_{ii} > 0$ and $0 \le v_{ij} < v_{jj}$.

Lemma 3.1. *We have*

$$\mathrm{gap}(\Lambda, \boldsymbol{l}) \le l_1 v_{11} + \cdots + l_d v_{dd} - \sum_{i=1}^{d} l_i\,. \tag{3.2}$$

Proof. Note that the Gram-Schmidt orthogonalisation of $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d$ has the form

$$\hat{\boldsymbol{b}}_1 = v_{11}\boldsymbol{e}_1, \hat{\boldsymbol{b}}_2 = v_{22}\boldsymbol{e}_2, \ldots, \hat{\boldsymbol{b}}_d = v_{dd}\boldsymbol{e}_d\,. \tag{3.3}$$

Hence, the box $B = B(\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d)$ can be written as

$$B = [0, v_{11}) \times \cdots \times [0, v_{dd})\,.$$

By Lemma 2.1, $B + \Lambda$ is a tiling of $\mathbb{R}^d$. In particular, $B + \Lambda$ covers $\mathbb{R}^d$.

Since $B \subset (l_1 v_{11} + \cdots + l_d v_{dd})\Delta_{\boldsymbol{l}}$, we have

$$\rho(\Delta_{\boldsymbol{l}}, \Lambda) \le l_1 v_{11} + \cdots + l_d v_{dd}\,.$$

By (2.1), the bound (3.2) holds.

□

Consider the simplex $\Delta = \mathrm{conv}\,\{\mathbf{1}, \boldsymbol{p}_1, \ldots, \boldsymbol{p}_d\}$, where $\mathrm{conv}\,\{\cdot\}$ denotes the convex hull, $\mathbf{1}$ is the all-one vector and

$$\begin{aligned} \boldsymbol{p}_1 &= (\det(\Lambda), 1, \ldots, 1)^t\,,\\ \boldsymbol{p}_2 &= (1, \det(\Lambda), \ldots, 1)^t\,,\\ &\vdots\\ \boldsymbol{p}_d &= (1, 1, \ldots, \det(\Lambda))^t\,. \end{aligned}$$

It is easy to see that

$$\{\boldsymbol{x} \in \mathbb{R}^d_{\ge 1} : x_1 \cdots x_d = \det(\Lambda)\} \subset \Delta\,. \tag{3.4}$$

Since Δ is a convex bounded polyhedron, the maximum of the linear function $\boldsymbol{l} \cdot \boldsymbol{x}$ over Δ is attained at one of its vertices $\mathbf{1}, \boldsymbol{p}_1, \ldots, \boldsymbol{p}_d$. Therefore

$$\max\{\boldsymbol{l} \cdot \boldsymbol{x} : \boldsymbol{x} \in \Delta\} = (\det(\Lambda) - 1)\|\boldsymbol{l}\|_\infty + \sum_{i=1}^{d} l_i\,. \tag{3.5}$$

Since $v_{11} \cdots v_{dd} = \det(\Lambda)$, we obtain by (3.4) and (3.5)

$$l_1 v_{11} + \cdots + l_d v_{dd} \le (\det(\Lambda) - 1)\|\boldsymbol{l}\|_\infty + \sum_{i=1}^{d} l_i\,. \tag{3.6}$$

By (3.2) and (3.6) we obtain (1.4).

4. Proof of Theorem 1.2

In this section we will use classical results of Brauer [4] and Brauer and Seelbinder [5] to prove Theorem 1.2. In the course of the proof we also show that the bound (3.2) in Lemma 3.1 is sharp.

Let $\boldsymbol{a} = (a_1, \ldots, a_{d+1})^t \in \mathbb{Z}^{d+1}_{>0}$ be a positive integer vector with coprime entries, that is $\gcd(a_1, \ldots, a_{d+1}) = 1$. Consider the lattice $\Lambda = \Lambda(\boldsymbol{a})$ defined as

$$\Lambda = \{\boldsymbol{x} \in \mathbb{Z}^d : a_2 x_1 + \cdots + a_{d+1} x_d \equiv 0 \,(\bmod\, a_1)\}\,.$$

Note that $\det(\Lambda) = a_1$ (see e.g. Corollary 3.2.20 in [8]).

Let

$$f_1 = a_1, f_2 = \gcd(a_1, a_2), \ldots, f_{d+1} = \gcd(a_1, a_2, \ldots, a_{d+1}) = 1\,.$$

Consider the basis $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d$ of the lattice Λ given by (3.1). The next lemma shows that the Gram-Schmidt box $B(\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d)$ is entirely determined by the parameters f_i.

Lemma 4.1. *The box $B = B(\boldsymbol{b}_1, \ldots, \boldsymbol{b}_d)$ has the form*

$$B = \left[0, \frac{f_1}{f_2}\right) \times \left[0, \frac{f_2}{f_3}\right) \times \cdots \times \left[0, \frac{f_d}{f_{d+1}}\right)\,.$$

Proof. By the definition of the box B and (3.3), it is enough to show that

$$v_{11} = \frac{f_1}{f_2}, v_{22} = \frac{f_2}{f_3}, \ldots, v_{dd} = \frac{f_d}{f_{d+1}}\,. \tag{4.1}$$

Recall that Λ_i denotes the sublattice of Λ generated by the first i basis vectors $\boldsymbol{b}_1, \ldots, \boldsymbol{b}_i$. We can write Λ_i in the form

$$\Lambda_i = \left\{(x_1, \ldots, x_i, 0, \ldots, 0) \in \mathbb{Z}^d : \frac{a_2}{f_{i+1}} x_1 + \cdots + \frac{a_{i+1}}{f_{i+1}} x_i \equiv 0 \left(\bmod\, \frac{a_1}{f_{i+1}}\right)\right\}\,.$$

Hence, $\det(\Lambda_i) = a_1/f_{i+1}$. On the other hand, (3.1) implies that $\det(\Lambda_i) = v_{11} v_{22} \cdots v_{ii}$. Since $\det(\Lambda) = v_{11} v_{22} \cdots v_{dd} = a_1$, we have $f_{i+1} = v_{i+1\,i+1} \cdots v_{dd}$ for $i \le d-1$, which immediately implies (4.1).

□

The *Frobenius number* $\mathrm{F}(\boldsymbol{a})$ associated with the integer vector $\boldsymbol{a}$ is the largest integer number which cannot be represented as a nonnegative integer combination of the a_i's. The problem of finding $\mathrm{F}(\boldsymbol{a})$ has a long history and is traditionally referred to as the *Frobenius problem*, see e. g. [18].

Set $\boldsymbol{l}(\boldsymbol{a}) = (a_2, \ldots, a_{d+1})^t$. It is known (see e.g. proof of Theorem 1.1 in [1] and Section 5.1 in [17]) that

$$\mathrm{gap}(\Lambda(\boldsymbol{a}), \boldsymbol{l}(\boldsymbol{a})) = \mathrm{F}(\boldsymbol{a}) + a_1\,. \tag{4.2}$$

Note also that, in this special case, (2.1) follows from Theorem 2.5 of Kannan [15].

By Lemma 4.1, the bound (3.2) for $\mathrm{gap}(\Lambda(\boldsymbol{a}), \boldsymbol{l}(\boldsymbol{a}))$ given by Lemma 3.1 can be obtained by replacing $\mathrm{F}(\boldsymbol{a})$ on the right hand side of (4.2) by the estimate

$$\mathrm{F}(\boldsymbol{a}) \le C(\boldsymbol{a}) := a_2 \frac{f_1}{f_2} + \cdots + a_{d+1} \frac{f_d}{f_{d+1}} - \sum_{i=1}^{d+1} a_i \tag{4.3}$$

given in Brauer [4]. It should be remarked here that Brauer [4] rather worked with the quantity $\mathrm{F}^{+}(\boldsymbol{a}) = \mathrm{F}(\boldsymbol{a}) + \sum_{i=1}^{d+1} a_i$, the largest number which cannot be represented as a *positive* integer combination of the a_i's. Brauer [4] and, subsequently, Brauer and Seelbinder [5] proved that the bound (4.3) is sharp and obtained the following necessary and sufficient condition for the equality $\mathrm{F}(\boldsymbol{a}) = C(\boldsymbol{a})$.

Lemma 4.2 (see Theorem 5 in [4] and Theorem 1 in [5])**.** *Let* $\boldsymbol{a} = (a_1, \ldots, a_{d+1})^t \in \mathbb{Z}^{d+1}_{>0}$, $d \ge 2$, *with* $\gcd(a_1, \ldots, a_{d+1}) = 1$. *Then* $\mathrm{F}(\boldsymbol{a}) = C(\boldsymbol{a})$ *if and only if for* $m = 3, 4, \ldots, d+1$ *the integer* a_m/f_m *is representable in the form*

$$\frac{a_m}{f_m} = \sum_{i=1}^{m-1} \frac{a_i}{f_{m-1}} y_{mi} \tag{4.4}$$

with integers $y_{mi} \ge 0$.

For $s = 2, 3, \ldots, d+1$, let

$$\boldsymbol{a}^{(s)} = \left(\frac{a_1}{f_s}, \ldots, \frac{a_s}{f_s} \right)^t .$$

The condition (4.4) is satisfied, in particular, if

$$\frac{a_m}{f_m} > \mathrm{F}(\boldsymbol{a}^{(m-1)}) .$$

Hence the bound (3.2) in Lemma 3.1 is sharp and the vectors $\boldsymbol{a}$ satisfying (4.4) can be easily constructed. To show that (1.4) is sharp, we will use a special case of Lemma 4.2, that regards the optimality of the Schur's upper bound for the Frobenius number (see [4]). Suppose that a vector $\boldsymbol{a} \in \mathbb{Z}^{d+1}_{>0}$ with coprime entries satisfies the following conditions:

$$\begin{array}{ll} (i) & D = a_1 \le a_2 \le \cdots \le a_{d+1} \,, \\ (ii) & a_2 \equiv a_3 \equiv \cdots \equiv a_r (\bmod a_1) \text{ for some index } r \ge 3 \,, \\ (iii) & a_{r+1} = a_{r+2} = \cdots = a_{d+1} \,. \end{array} \tag{4.5}$$

By Theorem 3 in [4] (cf. Theorem 4 ibid.) conditions (4.5) imply that $\mathrm{F}(\boldsymbol{a}) = a_1 a_{d+1} - a_1 - a_{d+1}$. Hence $\mathrm{gap}(\Lambda(\boldsymbol{a}), \boldsymbol{l}(\boldsymbol{a})) = (a_1 - 1) a_{d+1} = (D-1)\|\boldsymbol{l}\|_\infty$. The theorem is proved.

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