LLL reducing with the most significant bits

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ABSTRACT
Let $B$ be a basis of a Euclidean lattice, and $\tilde{B}$ an approximation thereof. We give a sufficient condition on the closeness between $B$ and $\tilde{B}$ so that an LLL-reducing transformation $U$ for $\tilde{B}$ remains valid for $B$. Further, we analyse an efficient reduction algorithm when $B$ is itself a small deformation of an LLL-reduced basis. Applications include speeding-up reduction by keeping only the most significant bits of $B$, reducing a basis that is only approximately known, and efficiently batching LLL reductions for closely related inputs.

Categories and Subject Descriptors
I.1.2 [Symbolic and Algebraic Manipulation]: Algorithms; F.2.1 [Analysis of Algorithms and Problem Complexity]: Numerical Algorithms and Problems; G.1.3 [Numerical Linear Algebra]: Conditioning

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Lattice basis reduction, LLL, floating point arithmetic

1. INTRODUCTION
We consider the problem of computing a reducing transformation for a Euclidean lattice basis $B$ using an approximation $\tilde{B}$ to $B \in \mathbb{R}^{m \times n}$. The necessary background on basis reduction is given in Section 2.2. Our notion of reduction is a variation, robust to perturbations, of the LLL reduction introduced by Lenstra, Lenstra and Lovász in [10]. We assume that the basis vectors are given by the columns of a full column rank matrix $B$. We establish a bound on the closeness between $\tilde{B}$ and $B$ so that if $U$ is a reducing transformation for $\tilde{B}$, i.e., the matrix $BU$ is LLL-reduced, then $BU$ also is reduced.

A main application is to compute a reducing transformation using only a limited number of bits of the input basis, hence possibly at a lower cost than using the entire initial basis. An approach for LLL-reducing a basis $B$ may then be: 1) use the bound and compute an appropriate rounding precision, and deduce an approximation $\tilde{B}$ sufficiently close to $B$; 2) compute $U$ by reducing $\tilde{B}$; 3) output $BU$. We follow this general approach for designing Algorithm 1.

We then develop a column scaling strategy for handling cases where the input basis vectors have unbalanced magnitudes. Indeed, in addition to mastering the bit-size of the inputs, dealing with homogeneous magnitudes is often better for lowering the computational cost: as far as we are aware of, no known LLL-reduction algorithm preserves the small bit-size of a “floating-point" basis during the execution, if the magnitudes of the columns differ. A scaling is a pre-processing of the basis $B$ that provides with a “more balanced" matrix $B'$ that is also appropriate for computing a reducing transformation. In this purpose we design Algorithm 2 that may be used as Step 2') in the general LLL-reducing scheme above. We note that after both the approximation and the scaling processes, “almost any” LLL-reducing scheme above. We note that after both the approximation and the scaling processes, “almost any” LLL-reducing algorithm could be used at Step 2) or 2') for computing the reducing transformation.

An important contribution in the study of approximation conditions for preserving reducing transformations has been made by Buchmann in [2]. In the rest of the paper the matrix norm induced by the Euclidean norm is denoted by $\| \cdot \|$.

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$\Delta B$ satisfies $\max_{i \leq n} \frac{\|\Delta b_i\|}{\|b_i\|} \leq \varepsilon$, where $\varepsilon \geq 0$ is small. Hence $B + \Delta B$ is an approximation to $B$ with small columnwise relative precision. In the case of approximate computations, the error bound $\varepsilon$ is of the order of $2^{-p}$, where $p$ is a working precision. Our type of approximations models matrix truncation with small error relatively to each column magnitude. This choice is appropriate for taking into account the backward rounding errors of standard numerical QR-factorization algorithms such as Householder’s, that are at the heart of fast reducing algorithms. It also preserves LLL-reducedness, as shown in [4]. To introduce our results, we need to define the QR-factorization. Let $B \in \mathbb{R}^{m \times n}$ be full column rank. There exists a unique pair $(Q, R)$ such that

$$B = Q \cdot R, \quad Q \in \mathbb{R}^{m \times n}, \quad R \in \mathbb{R}^{n \times n},$$

the columns of $Q$ are orthonormal and the matrix $R$ is upper-triangular with positive diagonal coefficients. The matrices $Q$ and $R$ are respectively called the $Q$-factor and $R$-factor of $B$. For insights into perturbation analysis we may refer the reader to Higham [6], and to [3, 4] in the context of QR-factorization.

Our first result is an improved bound that characterizes which columnwise approximations $B + \Delta B$ to $B$ are allowed such that a reducing transformation $U$ for $B + \Delta B$ remains valid for $U$. Instead of using the defect and the lattice minima, we relate the sufficient precision $1/\varepsilon$ to the quantity

$$\text{cond}(R) = \|R\| \cdot |R^{-1}|.$$  

This quantity is defined for any square invertible matrix, and may be viewed as a condition number for the problem of computing $R$. (See, e.g., Zha [19] and Higham [6] Ch. 19.)

In Theorem 1 we show that as soon as

$$\max_{i \leq n} \frac{\|\Delta b_i\|}{\|b_i\|} \leq \frac{1}{cn^\beta \text{cond}(R)},$$

for a constant $c$ that may be made explicit and a constant $\beta$ that can be chosen arbitrarily close to 2, if $U$ reduces $B + \Delta B$, then $U$ also reduces $B$. Because of the approximation, the matrix $BU$ is LLL-reduced for parameters slightly weaker than those for which $(B + \Delta B)/U$ is reduced. However, one may ensure that the parameters are degraded by an arbitrarily small amount (by increasing $c$), and the main relevant properties of LLL-reduced bases are preserved, such as those reminded in Lemma 2.

The bound above indicates that taking $p = 2 \log \text{cond}(R) + n(1+\varepsilon) + O(\log m)$ bits of precision on the input basis $B$ suffices for an arbitrarily small $\varepsilon$. We will see, with Lemma 3 that $\text{cond}(R)$ is a more accurate measure than the orthogonality defect $\text{od}(B)$. Indeed, the condition we propose is never more restrictive (up to a $O(\log n)$ additive term) and may be much less so than Buchmann’s. In particular, we exhibit a family of bases for which we divide the number of required bits by $\Omega(n)$.

A direct application is an interesting situation considered in [1]. It concerns matrices $B$ whose R-factor satisfies $|r_{ij}| \leq \eta r_{ii}$ for $\eta \geq 0$ (see Definition 1 with $\theta = 0$), and for which the ratio $h = \frac{\max_{i \leq n} |r_{ii}|}{\min_{i \leq n} |r_{ii}|}$ is bounded. In Theorem 2 we show that in this case $\log \text{cond}(B) \leq n \log(1+\eta) + \log h$. It follows that $\approx n(1+2\log(1+\eta)) + 2 \log h + O(\log m)$ bits of columnwise precision suffice for computing a reducing matrix. The bound is especially interesting when $h \ll \log \|B\|$, such as in [1] Sec. 3.2. The authors of [1] use a constant factor fewer bits than we do (they indeed work with about $\log h$ bits). However, their study is restricted to the first vector of the output basis, which is shown to be no more than a factor $2^O(n)$ longer than that of an LLL-reduced basis, compared to the $n$th root of the lattice determinant (see Section 2.2 for the definition of the lattice determinant). This interesting result is an example of transfer between the precision and the quality of the reduction. It also demonstrates the accuracy of our all-purpose bound.

It is essential to note that the ratio $h$ given by the diagonal of $R$ may not be relevant in general for indicating allowed truncations. Indeed, a large $h$ may not imply a large $\text{cond}(R)$, as shown by LLL-reduced bases, which can have arbitrarily large ratios $h$ but always satisfy $\text{cond}(R) = 2^{O(n)}$ (see Lemma 9).

Our second contribution is an LLL-reduction specifically designed for (floating-point) matrices of the form $B = M_B \cdot E_B$, where $M_B \in \mathbb{Z}^{m \times n}$ is full column rank and $E_B = \text{diag}((2^\ell)^s)$, with $\ell \in \mathbb{Z}$ for all $i$. Such matrices include the ones obtained by columnwise rounding. If the norms of the columns are unbalanced (i.e., the $\ell_i$’s have different orders of magnitude), the compactness of the representation may be lost when applying an LLL-reduction algorithm to $B$, as the columns get mixed. To circumvent this issue, we propose an algorithm (Algorithm 2) that applies a column scaling $D^{-1} \cdot M_BE_B$ before calling an LLL-reduction algorithm on $B' = M_BE_BD^{-1}$. The obtained transformation $U$ for $B'$ is then mapped to a transformation $D^{-1} \cdot UD$ for $B$.

Concerning the correctness of the approach, the main difficulty is to find a scaling $D$ such that $D^{-1} \cdot UD$ is unimodular and indeed reduces $B$. This is solved by numerically estimating the diagonal of the $R$-factor $R$ of $B$ and identifying blocks of consecutive vectors such that $\rho_{ii} \ll \rho_{jj}$ if $j$ belongs to a block subsequent to the one of $i$. These blocks are the main source of unbalancedness between the norms of the columns of $B$, and the computed scaling annihilates it. Our algorithm then relies on a “well-behaved” LLL-reduction algorithm that does not destroy the block structure (most known LLL-reduction algorithms are well-behaved, as explained in Section 5.1).

To measure the efficiency of the approach, the relevant quantity is the bit-size of the entries of $B'$ once converted to an integer matrix. To estimate it, we view $U = M_BE_B$ as a distortion $B = \Sigma C$ of an LLL-reduced matrix $C$, where $\Sigma \in \mathbb{R}^{m \times n}$ is non-singular. We then prove, in Theorem 3 that if $\sigma_1 \geq \ldots \geq \sigma_m$ are the singular values of $\Sigma$, then the bit-size of $B'$ is an $O \left( n + \log \|M_B\| + \log \prod_{i \leq [n/2]} \sigma_{2i-1} \right)$. Several $\Sigma$’s may exist so that $\Sigma^{-1}B$ is LLL-reduced, and one may optimize the choice of $\Sigma$ to lower $\prod_{i \leq [n/2]} \sigma_{2i-1}$. A direct application is to LLL-reduce for strong LLL parameters, a basis that is already reduced for some weak LLL parameters. This is a tempting approach in practice, as LLL-reducing for weak parameters is typically much faster. This strategy is mentioned, e.g., in [5, Se. 2.6.1] and [9, pp. 70–72]. Here $\Sigma$ is the identity and $\prod_{i \leq [n/2]} \sigma_{2i-1} = 1$. Another particular case is $\Sigma = \text{diag}(2^2, \ldots, 1)$, for which we have $\prod_{i \leq [n/2]} \sigma_{2i-1} = 2^2$. This is used in the polynomial factoring algorithm of [7] as well as at the bottom of the recursion in the $\tilde{L}$ algorithm 15.

Finally, our algorithm may be used to batch reductions of...
closely related lattices \((L_k)\) described by bases \((B_k)\) such that \(L_{k+1} = \Sigma L_k\) for all \(k\), where the \(\Sigma_k\)'s have balanced singular values. One may then LLL-reduce \(B_1\), and, for \(k \geq 1\), use the transformation matrix \(U_k\) computed for \(B_k\) before calling our algorithm on \(B_{k+1} U_k = \Sigma_k(B_k U_k)\). This strategy is used, e.g., in communications theory and cryptanalysis applications of LLL [13]. Our algorithm could prove useful to accelerate and analyze these applications.

**Remark.** The present work generalizes several results previously investigated for the design of the \(L^\star\) algorithm [15]. Perturbation analyses and approximations indeed play a key role since \(L^\star\) heavily rely on well-chosen truncations. The results in [15] are essentially focused on LLL-reduced bases, and on specific deformations of such bases. The generalization here is a study with no restrictive assumptions on the initial basis \(B\).

**Notations.** If \(B\) is a real-valued matrix, then \(|B|\) (resp. \([B]\)) is the matrix obtained by replacing each entry of \(B\) by its absolute value (resp. the largest integer no greater than it). If \(B\) and \(B'\) are two matrices of identical dimensions, the relation \(B \leq B'\) must be understood as a componentwise bound. The notations \(|B|\) and \([B]\) respectively refer to the Frobenius and induced Manhattan norms of \(B\). If \(B\) is square and non-singular we define \(\kappa(B) = |B| \cdot |B^{-1}|\). Clearly, we have \(\text{cond}(B) \leq \kappa(B)\). If \((x_i)\) is a sequence of cardinality \(n\), let \(\text{diag}(x_i)\) denote the \(n \times n\) diagonal matrix whose diagonal entries are the \(x_i\)'s. The computational costs are given in terms of bit operations. We let \(\mathcal{M}(t)\) be the cost of multiplying two \(t\)-bit long integers. Finally, all logarithms are in base 2.

## 2. QR AND BASIS REDUCTION

We extensively rely on roundings and perturbations. We say that \(\hat{B}\) is an approximation to \(B\) of columnwise relative precision \(p \geq 0\) if \(\hat{B} - B = \Delta B\) satisfies max \(|\Delta|_{\hat{b}}|b| \leq 2^{-p}\).

Approximating real matrices by floating-point ones fits into this context. A precision-\(p\) floating-point number is of the shape \(m \cdot 2^e\) with \(m, e\) integers with \(|m| \leq 2^p - 1\). For any \(x \in \mathbb{R}\), there exists \(m, e\), with \(|m| \leq 2^p - 1\) such that \(|m \cdot 2^e - x| \leq 2^{-p}|x|\). We call \(m \cdot 2^e\) a precision \(p\) approximation to \(x\). If \(x\) is a non-zero integer with known bit-length, such an approximation may be computed in time \(O(p + \log(1 + \log|x|))\), and \(e\) has bit-length \(O(\log|\log x|)\).

An interesting matrix perturbation is columnwise rounding. Let \(B = (b_i)\) \(\in \mathbb{R}^{m \times n}\) be full column rank, and \(p\) be a non-negative integer. For each \(i \leq n\), let \(e_i\) be an integer such that \(0 \leq (2^{-p} - |e_i|) < 3/4\). Let \(E_B = 2^{-p} \text{diag}(2^{-p})\) and \(M_B = (B \cdot E_B^{-1})\). Then \(\Delta B = B - M_B E_B\) satisfies max \(|\Delta|_{\hat{b}}|b| \leq 2^{-p}\). We may therefore view \(M_E B = M_B E_B\) as a columnwise floating-point approximation to \(B\). Each entry of the mantissa matrix \(M_E\) is an integer of magnitude smaller than \(2^{p-1}\), and the matrix \(E_B\) may be represented on \(O(n \log \log |B| + |\log p|)\) bits, gives column exponents.

### 2.1 Numerical aspects of QR-factorization

The numerical aspects of QR-factorization have been extensively studied, and we refer the reader to [10, Ch. 19] for a comprehensive entry point to the topic. The following is an explicit variant of classical results.

**Lemma 1** ([1, Se. 6]). Let \(p \geq 0\) and \(B \in \mathbb{R}^{m \times n}\) be non-singular with R-factor \(R\). Let \(\hat{R}\) be the R-factor computed by Householder’s algorithm with floating-point precision \(p\). If \(80m2^{-p} < 1\), then there exists an orthogonal \(Q\) such that \(\hat{Q}R = \hat{R} + \Delta B\) with max \(|\Delta|_{\hat{b}}|b| \leq 80m2^{-p}\).

Given a matrix \(B\), the number of bit operations consumed by Householder’s algorithm for computing an approximation to the R-factor of \(B\) is \(O(mn^2(M(p) + \log \log |B|))\).

The backward stability lemma above is often combined with a sensitivity result, such as the one below, in order to obtain forward error bounds on the computed quantities.

**Lemma 2** (Adapted from [1, Th. 2.3]). Let \(B\) be full column rank in \(\mathbb{R}^{m \times n}\), and let \(R\) denote its R-factor. Let \(\Delta B \in \mathbb{R}^{m \times n}\). If \(\max_{|i|\leq n} \frac{|\Delta b_i|}{|b_i|} < 1/(12m\sqrt{\text{cond}(R)})\), then \(B + \Delta B\) is full column rank and its R-factor \(R + \Delta R\) satisfies \(\|\Delta R - R^{-1}\|_F \leq 6m\sqrt{\text{cond}(R)}\max_{|i|\leq n} \frac{|\Delta b_i|}{|b_i|}\).

**Proof.** The assertion on the rank follows from [1, Le. 2.2]. From the end of the proof of [4, Th. 2.3] with \(D = I\), we have \(\|\Delta R - R^{-1}\|_F < (\sqrt{6} + \sqrt{3})\sqrt{m}\sqrt{\text{cond}(R)}\max_{|i|\leq n} \frac{|\Delta b_i|}{|b_i|}\).

We will also use the following result on the effect of a matrix \(B\) of applying a distortion to \(B\).

**Lemma 3.** Let \(B \in \mathbb{R}^{m \times n}\) be full column rank and let \(R\) denote its R-factor. Let \(\Sigma \in \mathbb{R}^{m \times m}\) be non-singular, and let \(R'\) denote the R-factor of \(\Sigma B\). Then, for all \(i\), we have \(\|\Sigma\|^{-1} \leq \frac{\sqrt{\text{cond}(R')}}{\sqrt{\text{cond}(R)}}\).

**Proof.** The proof is adapted from the proof of [7, Le. 4]. Let \(V_i(B) = (b_i - \sum_{j<i} y_j b_i : y_1, \ldots, y_{i-1} \in \mathbb{R})\). Then \(r_{\mathbb{R}}\) is the norm of the shortest vector \(b\) in \(V_i(B)\). Now, the vector \(\Sigma b\) belongs to \(V_i(\Sigma B)\). As a result, we have \(r_{\mathbb{R}} \leq \|\Sigma b\| \leq \|\Sigma\| \cdot r_{\mathbb{R}}\). The proof that \(r_{\mathbb{R}} \geq \frac{1}{\sqrt{\text{cond}(\Sigma)}}\) is analogous.

### 2.2 Lattices and LLL basis reduction

A lattice \(L\) is the set of integer combinations of linearly independent vectors in a euclidean space \(\mathbb{R}^n\): any lattice may be written as \(L = L(B) = \mathbb{Z}^n\), for some full column rank matrix \(B \in \mathbb{R}^{m \times n}\). The columns of \(B\) are said to form a basis of \(L\). If the lattice dimension satisfies \(n \geq 2\), the lattice admits infinitely many lattice bases, related by unimodular matrices (i.e., square integer matrices of determinant \(\pm 1\)): for two full column rank matrices \(B, C \in \mathbb{R}^{m \times n}\), we have \(\mathbb{Z}^n = \mathbb{Z}^n\) if and only if there exists a unimodular matrix \(U\) such that \(C = B \cdot U\).

The sparsity of a lattice \(L\) may be quantified by its successive minima, defined as \(\lambda_i(L) = \inf(r : \dim(\text{span}(L \cap B(0, r)) \geq i)\), for all \(i \leq n\). It may also be quantified with the lattice determinant det \(L = \prod_{i=1}^n r_i\), where \(R\) is the R-factor of any basis of \(L\).

In 1982, Lenstra et al. [10] introduced the notion of LLL-reduction of a lattice basis and the LLL-algorithm. If a basis is LLL-reduced, then it is short with respect to the minima of the spanned lattice, and, further, such a basis can be efficiently found using the LLL algorithm. Here we use a variation of LLL-reduction that is more suited to numerical computations.

**Definition 1** ([1, Def. 5.3]). Let \(\Xi = (\delta, \eta, \theta)\) with \(\eta \in (1/2,1), \delta \in (0,1]\), and \(\theta \in (\gamma^2, 1)\). Let \(B \in \mathbb{R}^{m \times n}\) be non-singular with QR-factorization \(B = Q \cdot R\). The matrix \(B\) is \(\Xi\)-LLL-reduced if:
• for all $i < j$, we have $|r_{ij}| \leq \eta r_{ij} + \theta r_{ij}$ ($B$ is said size-reduced);

• for all $i$, we have $\delta \cdot r_{ii}^2 \leq r_{ii}^2 + r_{ii+1}^2$ ($B$ is said to satisfy Lovász' conditions).

Let $\Xi = (\delta, \eta, \theta)$ and $\Xi_w = (\delta_w, \eta_w, \theta_w)$ be valid LLL-parameters. We say that $\Xi_w$ is weaker than $\Xi$ and write $\Xi \preceq \Xi_w$ if $\delta \geq \delta_w, \eta < \eta_w$ and $\theta < \theta_w$. If a basis is $\Xi$-LLL-reduced and if $\Xi \preceq \Xi_w$, then it is also $\Xi_w$-LLL-reduced. This LLL-reduction variant is as powerful as the classical definition.

**Lemma 5** (Adapted from [4, Cor. 5.7]). For any valid sets of parameters $\Xi = (\delta, \eta, \theta)$ and $\Xi_w = (\delta_w, \eta_w, \theta_w)$ with $\Xi_w \preceq \Xi$, there exists a constant $c > 0$ (that may be made explicit) such that the following holds. For any $\Xi$-LLL-reduced $B \in \mathbb{R}^{m \times n}$ and any $\Delta B$ satisfying $\max_{i} \frac{\|b_i\|}{\|b_i\|_{\Xi}} \leq 1/(c^2(1 + \eta + \theta)\alpha^2)$ where $\alpha$ is as in Lemma 4 the basis $B + \Delta B$ is $\Xi_w$-LLL-reduced.

The $L^3$ algorithm from [10] allows one to compute an LLL-reduced basis of the lattice spanned by a given $B \in \mathbb{Z}^{m \times n}$ in time $O\left(n^4 \log^2 \|B\|_{\alpha}^{M(\log \|B\|_{\alpha})} \right)$ (see [8]). The $L^2$ and H-LLL algorithms from [11, 12] achieve it within $O(nM(n+\log \|B\|)\log \|B\|)$ bit operations, while the $L^3$ from [15] runs in time $O(mn\log(n + \log \|B\|))$.

Finally, we will use the following generalization of Le. 5 to arbitrary bases, which provides a bound on the size of the unimodular matrix between any basis of a lattice and an LLL-reduced basis of the same lattice.

**Lemma 6.** Let $B \in \mathbb{R}^{m \times n}$ be full column rank. Let $\Xi$ be a valid LLL-parameter, as in Lemma 4 and $U$ such that $C = BU$ is $\Xi$-reduced. We have:

\[ \forall i, j : |u_{ij}| \leq m^3 \alpha^n \text{cond}(R) \frac{r_{jj}}{r_{ii}} \]

where $R$ and $R'$ respectively denote the $R$-factors of $B$ and $C$.

**Proof.** Let $B = QR$, $C = Q'R'$ be the QR-factorizations of $B$ and $C$, respectively. Then

\[ U = R^{-1}Q'R' = \text{diag}(r_{ii}^{-1})\overline{R}^{-1}Q' \overline{Q'} \text{diag}(r_{ii}) \]

with $\overline{R} = R \cdot \text{diag}(1/r_{ii})$ and $\overline{Q'} = Q' \cdot \text{diag}(1/r_{ii})$. We have $|\overline{R}^{-1}| \leq |R|^{-1}|R'| \leq \text{cond}(R) |T|$, where $t_{ij} = 1$ if $i < j$ and $t_{ij} = 0$ otherwise. By Lemma 4 we have $|\overline{R}| \leq \alpha T$. We also have $|Q||Q'| \leq M$, where $m_{ij} = 1$ for all $i, j$. Using the triangular inequality, we obtain:

\[ |U| \leq \text{cond}(R) \alpha^n \cdot \text{diag}(r_{ii}^{-1})T M^4 MT \text{diag}(r_{ii}) \leq mn^2 \alpha^n \cdot \text{cond}(R) \cdot \text{diag}(r_{ii}^{-1}) \text{diag}(r_{ii}) \]

where $N$ is the all-1 matrix with appropriate dimensions.

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**3. WELL-CONDITIONED MATRICES**

As we have seen, the quantity $\text{cond}(\cdot)$ plays a role both for the sensitivity of the $R$-factor under columnwise perturbations (Lemma 2) and for the size of the unimodular transformation between a lattice basis and an LLL-reduced basis of the same lattice (Lemma 6). It is therefore interesting to investigate sufficient conditions to ensure a small value of $\text{cond}(\cdot)$.

**Lemma 7.** Let $B \in \mathbb{R}^{m \times n}$ full column rank and $\Xi \in \mathbb{R}^{m \times n}$ non-singular. Let $R$ and $\Gamma'$ respectively denote the $R$-factors of $B$ and $\Sigma B$. Then $\text{cond}(R') \leq mn\|\Sigma\|\text{cond}(R)$.

Further, if $B$ and $B'$ are square and upper-triangular, then $\text{cond}(R') \leq \kappa(\Sigma)\text{cond}(R)$.

**Proof.** Write $B = QR$ (resp. $EB = Q'\Gamma'$), where the columns of $Q$ (resp. $Q'$) are orthogonal. The first result follows from the equation $|R'||R^-1| = ||(Q'T \Sigma Q)R| \cdot |R'|^{-1}|Q'T \Sigma Q||^{-1}$ and the triangular inequality. The proof simplifies when $Q$ and $Q'$ are square, as in that case we have $||Q'T \Sigma Q|| = ||\Sigma||$ and $||Q'T \Sigma Q||^{-1} = ||\Sigma||^{-1}$.

As a corollary, we obtain the fact that a small columnwise perturbation cannot increase $\text{cond}(\cdot)$ by much.

**Lemma 8.** Let $B \in \mathbb{R}^{m \times n}$ full column rank with $R$-factor $R$, and $\Delta B \in \mathbb{R}^{m \times n}$. If we have max $\frac{\|b_i\|}{\|b_i\|_{\Xi}} < 1/(12m\sqrt{n}\text{cond}(R))$, then $B + \Delta B$ is full column rank and its $R$-factor $R + \Delta R$ satisfies $\text{cond}(R + \Delta R) \leq 4\text{cond}(R)$.

**Proof.** Write $R + \Delta R = \Sigma R$, with $\Sigma = I + \Delta \Sigma \cdot R^{-1}$. By Lemma 2, we know that $\|\Delta R \cdot R^{-1}\| \leq \|\Delta R\| \|R^{-1}\| \leq 6m\sqrt{n}\text{cond}(R) \max_{i} \frac{\|b_i\|}{\|b_i\|_{\Xi}}$. Thanks to the assumption on max, $\|\Sigma b_i\|/\|b_i\|$, we obtain that $\Sigma$ is non-singular. Further $\|\Sigma\| \leq 2$ and $\|\Sigma^{-1}\| \leq \|I + \sum_{k \geq 1}(\Delta R)^k\| \leq 2$. As a result, we obtain $\kappa(\Sigma) \leq 4$. Lemma 7 provides the result.

The following result shows that any LLL-reduced basis has a small $\text{cond}(\cdot)$.

**Lemma 9.** (4, Le. 5.5). Let $\Xi = (\delta, \eta, \theta)$ be any valid set of LLL-parameters. If $B \in \mathbb{R}^{m \times n}$ is $\Xi$-LLL-reduced and $R$ is its $R$-factor, then $\text{cond}(R) \leq \left(\frac{1}{\sqrt{\delta - \eta}}\right)^{\min\{a, 1\}} \left(1 + \eta + \theta\right)^n$, with $a$ as in Lemma 7.

In fact, LLL-reducedness is a much stronger assumption than needed, for cond($R$) to be bounded by $2^\Omega(n)$. A weaker assumption is used in the following result. Note that the assumption is satisfied for LLL-reduced bases, by Lemma 2 applied to square diagonal sub-blocks of the R-factor.

**Lemma 10.** Let $B \in \mathbb{R}^{m \times n}$ be full column rank with $R$-factor $R$. Assume that there exists $\alpha > 1$ such that for all $i < j$, we have $|r_{ij}| \leq \alpha^i-1 r_{jj}$. Then $\text{cond}(R) \leq \frac{\alpha^2}{(\alpha^2-1)\sqrt{4\alpha^2-1}}(2^\Omega(n))$.

**Proof.** Write $\overline{R} = R \cdot \text{diag}(r_{ii}^{-1})$. We have cond($R$) = cond($\overline{R}$) $\leq \kappa(\overline{R})$. A direct computation shows that $|\overline{R}| \leq (\sum_{i=1}^n \sum_{j=1}^n \alpha^{2j})^{1/2} \leq (\sum_{i=1}^n \alpha^2)^{1/2} \leq \alpha^{n+1}/\alpha^{n-1}$. It now suffices to bound $|\overline{R}^{-1}|$ from above.

Write $\overline{R} = I + M$, where $M$ is the matrix having same elements as $\overline{R}$ but with zeroed diagonal coefficients. We have
\[ \mathbf{R}^{-1} = (I + M)^{-1} = \sum_{0 \leq k < n} (-M)^k. \] Using the triangle inequality, we obtain that \( |\mathbf{R}^{-1}| \leq \sum_{0 \leq k < n} |M|^k \). Let \( J \) denote the \( n \times n \) matrix such that \( J_{ij} = 1 \) if \( i = j \), and \( J_{ij} = 0 \) otherwise. By assumption, we have \( |M| \leq \alpha \sum_{0 \leq k < n} (\alpha J) = \alpha^2 J(I - \alpha J)^{-1}. \) As a consequence:
\[
|\mathbf{R}^{-1}| \leq \sum_{0 \leq k < n} (\alpha^2 J(I - \alpha J)^{-1})^k
= (I - \alpha^2 J(I - \alpha J)^{-1})^{-1}
= (I - \alpha^2 J(I - \alpha J)^{-1})^{-1}
\leq \sum_{0 \leq k < n} (\alpha + \alpha^2)^k K \leq \sum_{0 \leq k < n} (2\alpha^2)^k K.
\]
We derive that \( |\mathbf{R}^{-1}| \leq \left( \sum_{i=0}^{n-1} (2\alpha^2)^k \right)^{1/2} \leq \frac{2\alpha^2 n}{\sqrt{4\alpha^2 + 1}}, \) which leads to the result. \( \square \)

As discussed in the introduction, Buchmann provides in [2] a sufficient bound on the input precision to guarantee the correctness of the algorithm of the next section. The bound is at least logarithmic in the orthogonality defect \( \text{od}(B) = \prod \frac{1}{R_{ii} - 2} \) of the full column rank matrix \( B \in \mathbb{R}^{m \times n} \) with R-factor \( R \). Our sufficient condition involves a precision logarithmic in cond(\( B \)). The following lemma reveals the relationship between cond(\( B \)) and od(\( B \)).

**Lemma 11.** Let \( B \in \mathbb{R}^{m \times n} \) be full column rank and \( R \) be its R-factor. Then for all \( i \), we have \( \|b_i\| \leq r_i \text{cond}(R), \) implying that \( \text{od}(B) \leq \text{cond}(R)^{-1} \). Oppositely, we have cond(\( R \)):
\[
\text{cond}(R) \leq n^{3/2} \|B\| \|B^{-1}\| \leq n^{3/2} \|B\| \|B^{-1}\| \leq n^{3/2} \|B\| \|B^{-1}\|.
\]

**Proof.** For each \( i \geq j \), the coefficient \( (i,j) \) of \( |R| \cdot |R^{-1}| \) is bounded from above by \( |r_{ij}|/r_i \) (when doing the inner product of the \( j \)th row of \( |R| \) with the \( i \)th column of \( |R^{-1}| \), the coefficient \( |r_{ij}| \) is multiplied with \( 1/r_i \)). This implies that \( \|b_i\| \leq \text{cond}(R) \) holds for all \( i \). Multiplying over varying \( i \) gives the first statement.

We now prove the second statement. The coefficient \( (i,j) \) of \( |R^2|^{-1} \) is bounded from above by \( \frac{1}{r_i} \prod_{k < j} \frac{1}{r_k} \frac{1}{R_{kk}} \) (this can be obtained by using the cofactors of \( R \) to compute \( |R^{-1}| \) and then applying Hadamard’s bound). As a result, we obtain that the coefficient \( (i,j) \) of \( |R^2|^{-1} \) is bounded from above by \( \sum_{0 \leq k < n} \frac{1}{r_i} \prod_{k < j} \frac{1}{R_{kk}} \), which is itself \( \leq \alpha \cdot \text{od}(B) \).

Finally, consider the \( n \)-dimensional upper triangular matrix \( R \) defined by \( r_{ij} = \alpha^{j-i+1} \), for \( \alpha > 1 \) arbitrary. By considering only the first row of \( R \), we obtain that \( \text{od}(R) \geq \alpha^{n(n-1)/2} \). Lemma 10 allows us to complete the proof. \( \square \)

Another class of bases with relatively small cond(\( \cdot \)) is given by upper triangular matrices \( B \) whose diagonal entries have balanced magnitudes, and which are size-reduced with \( \theta = 0 \) in Definition 4. If the largest ratio \( h \) between two diagonal entries is small, then as shown by next lemma, the quantity cond(\( B \)) \( \leq h^{2/(n)} \) may be thought as small. (A geometric interpretation is given in [4] Se. 3.3.)

**Lemma 12.** Let \( B \in \mathbb{R}^{n \times n} \) be an upper triangular, invertible matrix with the property that for all \( i < j \) we have \( |b_{ij}| \leq \eta |b_{ii}| \), for some \( \eta \geq 0 \). Then we have cond(\( B \)) \( \leq 2n(1 + \eta)^{n-1} \max_{i \neq j} \frac{|b_{ii}|}{|b_{ij}|} \).

**Proof.** Let \( \mathbf{B} = \text{diag}(\{b_{ii}\}) \cdot B \). For all \( i < j \) we have \( |b_{ij}| \leq \eta |b_{ii}| \). Therefore, we have \( |\mathbf{B}^{-1}| \leq T^{-1} \), where \( T \in \mathbb{R}^{n \times n} \) is upper triangular with \( t_{ii} = 1 \) and \( t_{ij} = -\eta \) for \( i < j \) (see, e.g., [3] Th. 8.12). Since \( S = T^{-1} \) satisfies \( s_{ii} = 1 \) and \( s_{ij} = (1 + \eta)^{j-i-1} \) for \( i < j \) (see, e.g., [6] Eq. (8.4)), we obtain \( v_i = 2\eta(1 + \eta)^{j-i-1} \), for \( i < j \), where \( V = |T|^{-1} \). It follows that \( |V| \leq 2(1 + \eta)^{n-1} \) for all \( i \leq j \). Therefore, we may write cond(\( B \)) = \( |\text{diag}(b_{ii})| \cdot V \cdot |\text{diag}(b_{jj})| \leq 2(1 + \eta)^{n-1} \frac{|b_{ii}|}{|b_{jj}|} \), which shows the assertion. \( \square \)

Given an invertible \( B \in \mathbb{R}^{n \times n} \) with R-factor \( R \), one may estimate cond(\( R \)) in the following way. By [17], we have:
\[
\text{cond}(R) \leq n^{3/2} \|B\| \|B^{-1}\| \leq n^{3/2} \|B\| \|B^{-1}\| \leq n^{3/2} \|B\| \|B^{-1}\|.
\]

**4. Reducing by Rounding**

Our first main result is Theorem 4. We analyse the effect of applying to a lattice basis \( B \) a transformation matrix \( U \) reducing a perturbation \( B + \Delta B \) of \( B \). We rely on Lemma 13 which shows that a reducing transformation \( U \) for a given basis \( B \) remains a reducing transformation for any basis sufficiently close to \( B \). This result, with a backward stability flavor, is then applied to \( B + \Delta B \) for establishing the reducibility of \( B \).

**Lemma 13.** For any valid sets of LLL-parameters \( \Xi = (\delta, \eta, \theta) \) and \( \Xi_w = (\delta_w, \eta_w, \theta_w) \), with \( \Xi_w < \Xi \), there exists a constant \( c > 0 \) (that may be made explicit) such that the following holds. Let \( B \in \mathbb{R}^{m \times n} \) full column rank, \( R \) its R-factor, and \( U \) such that \( BU = \Xi \) LLL-reduced. Assume that \( \Delta B \in \mathbb{R}^{m \times n} \) satisfies \( \max_{i,j} \frac{|\Delta b_{ij}|}{|b_{ij}|} \leq 1/(c\alpha^{3/2} \text{cond}(R)) \) with \( b = (1 + \eta + \theta) \alpha^2 \) and \( \alpha \) as in Lemma 4. Then \( (B + \Delta)U \) is \( \Xi_w \)-reduced.

**Proof.** By Lemma 4, we have \( |u_{ij}| \leq m^\alpha \text{cond}(R) \frac{\alpha^{j-i+1}}{r_{ij}} \) for all \( i, j \), where \( R \) (resp. \( R' \)) is the R-factor of \( B \) (resp. \( C = BU \)). We obtain that \( \text{dec}(C) = \sum_{i,j} u_{ij} \Delta b_{ij} \) satisfies for all \( i,j \):
\[
|\Delta c_i| \leq \left( m^\alpha \text{cond}(R) \max_j \frac{\sum_{j} r_{ij} \|\Delta b_{ij}\|}{\|b_{ij}\|} \right) \sum_j r_{ij} \|\Delta b_{ij}\|.
\]
Now, by Lemma 11 we have that \( \|b_{ij}\| / r_{ij} \leq \text{cond}(R) \) holds for all \( j \). By using the fact that \( r_{ij} \leq |c_i| \), we derive that:
\[
\max_i \frac{|\Delta c_i|}{|c_i|} \leq m^\alpha \text{cond}^2(R) \max_j \frac{\sum_{j} \|\Delta b_{ij}\|}{\|b_{ij}\|}.
\]
Applying Lemma 4 to \( C \) and \( C + \Delta C \) provides the result. \( \square \)

The following result extends [15] to any full column rank matrix \( B \).
Theorem 1. For any valid sets of parameters $\Xi_w < \Xi$, there exists $c > 0$ (that may be made explicit) such that the following holds. Let $B \in \mathbb{R}^{m \times n}$ full column rank, $R$ its R-factor, and $\Delta B$ satisfying $\max\|\Delta B\| \leq 1/(cm^5\beta\text{cond}^2(R))$ with $\beta$ as in Lemma 13. Then if $U$ is such that $(B + \Delta B)U$ is $\Xi$-LLL-reduced, then $BU$ is $\Xi_w$-LLL-reduced.

Proof. By Lemma 8 we have $\text{cond}(R + \Delta R) \leq 4\text{cond}(R)$, where $R + \Delta R$ is the R-factor of $B + \Delta B$. We conclude by using Lemma 13 on $B + \Delta B$ with perturbation $-\Delta B$, to establish the reducedness of $B = (B + \Delta B) - \Delta B$. \qed

As a corollary of the theorem just above, Algorithm 1 is correct. Note that an upper bound of $\text{cond}(R)$ is required as part of the input, where $R$ denotes the R-factor of $B$. Such a bound may be derived from a priori information on $B$ (e.g., using Lemmata 3 and 8), or may be estimated, as explained at the end of Section 5.3. At Step 7, any LLL-reducing algorithm may be used. In the next section, we describe and analyze an LLL-reducing algorithm specifically designed for floating-point lattice bases $M_B E_B$, when they are themselves small distortions of LLL-reduced bases.

Input: $B \in \mathbb{R}^{m \times n}$ full column rank; valid LLL-parameters $\Xi_w$; $\chi \geq \text{cond}(R)$, where $R$ is the R-factor of $B$.
Output: A $\Xi_w$-reduced basis of the lattice spanned by $B$.
1. Choose valid LLL-parameters $\Xi > \Xi_w$.
2. Compute the constants $c$ and $\beta$ of Theorem 1.
3. Set $p := \lceil \log(4cm^7\beta^6\chi^2) \rceil$.
4. For each $i \leq n$, find $e_i \in \mathbb{Z}$ such that $\frac{2^{p+1}\|B e_i\|}{\|B e_i\|} \leq 3/4$.
5. Set $E_B := 2^{-p}\text{diag}(2^m)$.
6. Set $M_B := [B \cdot E_B]$.
7. Compute $U$ such that $(M_B E_B) \cdot U$ is $\Xi$-LLL-reduced.
8. Return $B \cdot U$.
Algorithm 1: LLL-reduction of $B$ using a columnwise floating-point approximation of $B$.

5. REDUCING BY SCALING

We now describe and analyze an algorithm for efficiently LLL-reducing floating-point lattice bases $M_B E_B$, such as the one involved at Step 7 of Algorithm 1. To LLL-reduce the floating-point matrix $M_B E_B$, we may interpret it as an integer matrix, and LLL-reduce that integer matrix. However, if the exponents are very unbalanced, the bit-size of $M_B E_B$ as an integer matrix (and hence the cost of the LLL-reduction) may be much higher than the bit-size of $M_B E_B$ as a floating-point matrix. Our algorithm scales the columns of $M_B E_B$, to obtain a matrix $M_B E_B D^{-1}$, so that the conversion to an integer matrix essentially preserves the small bit-size of the floating-point representation. The main difficulty to establish the correctness of the algorithm is to ensure that the transformation matrix $U$ when LLL-reducing $M_B E_B D^{-1}$ is relevant for LLL-reducing $M_B E_B$ (note that the spanned lattices are different).

Input: $M_B \in \mathbb{Z}^{m \times n}$ full column rank; $E_B = 2^{-p}\text{diag}(e_i)$ with $e_i \in \mathbb{Z}$ for all $i$; valid LLL-parameters $\Xi = (\delta, \eta, \theta)$; $\chi \geq \text{cond}(R)$, where $R$ is the R-factor of $M_B E_B$.
Output: A matrix pair $(U, D)$ such that $D^{-1}U D$ is unimodular, $(M_B E_B)(D^{-1}U D)$ is $\Xi$-LLL-reduced and $D = \text{diag}(2^m)$ with $d_i \in \mathbb{Z}$ for all $i$.
1. Set $p := 10 + \lceil \log(m^3\chi^2) \rceil$.
2. Call Householder’s algorithm on $M_B E_B$ with precision $p$, let $R$ be its output.
3. Set $i_0 := 1$ and $k := 1$.
4. For $i \leq n$, do: If $(\min_{j \neq i} \hat{r}_{ij} > (8/\theta) \cdot \max_{j < i} \hat{r}_{jj})$, then increment $k$ and set $i_k := i$.
5. For all $1 \leq k < k$, set $g_i := (\min_{j \leq i} \hat{r}_{ij}) / \max_{i < j \leq i} \hat{r}_{ij}$.
6. For all $1 \leq k < k$ and all $i \leq i_k$, set $d_i := e_i + \sum_{\ell < i} \lceil \log(g_i^2) \rceil$.
7. Set $D := \text{diag}(2^m)$, \text{* Column scaling */}
8. Set $\Xi := (\delta, \eta, \theta/2)$.
9. Compute $U$ s.t. $(M_B E_B D^{-1}) \cdot U$ is $\Xi$-LLL-reduced.
10. Return $(U, D)$.
Algorithm 2: LLL-reduction of a floating-point matrix $M_B E_B$ using column scaling.

Algorithm 2 can be divided into four main parts:

- Finding approximations of the diagonal coefficients of the R-factor of the input basis $M_B E_B$ (Steps 1-2) for determining the scaling.
- Finding blocks, delimited by the $r_{ii}$’s, of consecutive vectors in $M_B E_B$, such that typical LLL-reduction algorithms do not swap vectors between these blocks, because the $r_{ii}$’s increase (Steps 3-4). Appropriate gaps between blocks allow to preserve the block structure after the scaling, which is a key ingredient for ensuring that $U$ is block upper-triangular, and $D^{-1}U D$ is unimodular.
- Scaling the columns of $M_B E_B$, to shrink the eventual magnitude gaps between the $r_{ii}$’s of different blocks (Steps 5-7).
- LLL-reducing the scaled matrix (Steps 8-10).

5.1 Correctness

The following lemma ensures that the $\hat{r}_{ii}$’s are good approximations of the $r_{ii}$’s.

Lemma 14. The matrix $\hat{R}$ computed at Step 2 of Algorithm 2 satisfies $\max_i |\hat{r}_{ii} - r_{ii}| / r_{ii} \leq 1/2$.

Proof. Thanks to the choice of $p$, Lemmata 3 and 8 ensure that $\|\Delta R \cdot R^{-1}\| p \leq 2^m m^3\chi^2 2^{-p} \leq 1/2$, where $\Delta R = R - \hat{R}$. Looking at the diagonal coefficients of $\Delta R \cdot R^{-1}$ leads to the result. \qed

The next part of the algorithm aims at determining the column scalings to be applied to $M_B E_B$. The scalings are computed by grouping the columns of $M_B E_B$ according to the magnitudes of the $r_{ii}$’s. Columns with indices in $I_i = [i_r, i_{r+1})$ belong to the same block. By construction, the index $i_{r+1}$ is the smallest $i > i_r$ such that $\min_{j \geq i} \hat{r}_{ij} > (8/\theta) \cdot \max_{j < i} \hat{r}_{jj}$. Let the amplitude gap between two consecutive blocks $I_{r+1}$ and $I_{r}$ be $g_{r} := (\min_{j \geq i} \hat{r}_{ij}) / (\max_{j < i} \hat{r}_{ij})$. By construction of the blocks, and $\theta \leq 1$ (see Definition 1), we have $g_r \geq (8/\theta) \geq 8$ for all $r$. 
At Step 7, the column scaling is set to $D = \text{diag}(2^{d_i'})$, for each $\ell$ and each $i \in I$. By choice of the $d_i$’s, the block structure of $M_E B D$ is preserved for $M_E B D^{-1}$, but the gap between two blocks gets shrunk to at most a constant. The following result is a direct consequence of Lemma 14 and of the choice of the $d_i$’s.

**Lemma 15.** Let $R'$ denote the R-factor of $M_E B D^{-1}$. Then, for all $\ell$, we have $|\min_{i \in I} r_{\ell i}^* | \leq 32$.

At Step 9 of Algorithm 2, an LLL-reduction algorithm is called. It is required that this algorithm does not interfere with the block structure. In most LLL-reduction algorithms, the only operations performed on the current lattice basis $A$ are of two types: size-reductions of vectors (an integer linear combination of basis vectors $a_j$ with $j < i$ is subtracted from the basis vector $a_i$), and swaps (two consecutive basis vectors $a_{i-1}$ and $a_i$ are exchanged). We require that swaps occur only when $r_{\ell i} < r_{\ell i-1}$. This is the case for most known LLL-reduction algorithms, including [10, 16, 14, 13, 12]. We say that these LLL-reduction algorithms are well-behaved. Further, if the used LLL-reduction algorithm handles only integer matrices, we may multiply matrix $M_E B D^{-1}$ by a power of 2 to make it integral, and reduce the scaled matrix: the computed transformation $U$ will also be a valid LLL-reducing matrix for $M_E B D^{-1}$ as LLL-reducingness is invariant under basis scaling.

**Theorem 2.** Assuming the LLL-reducing algorithm used at Step 9 is well-behaved (as defined just above), Algorithm 2 is correct. In particular, the matrix $D^{-1} U D$ is unimodular and the matrix $(M_E B D)(D^{-1} U D)$ is $\Xi$-LLL-reduced.

**Proof.** Using Lemma 15 and the assumption on the LLL-reducing algorithm used at Step 9, we obtain that the computed matrix $U$ is block-upper triangular, in the following sense. For any $\ell, \ell'$, we define $U_{\ell \ell'} = (u_{ij})_{i \in I_{\ell}, j \in I_{\ell'}}$. Then for any $\ell \leq \ell'$, we have $U_{\ell \ell'} = 0$. Now, the diagonal coefficients of $D$ are non-decreasing powers of 2, and $d_i = d_i$ when $i, j$ belong to the same $I_{\ell'}$. As a result, the matrix $D^{-1} U D$ is integral: for $\ell \leq \ell'$, submatrix $U_{\ell \ell'}$ becomes $2^d_{\ell'-d_{\ell}} U_{\ell \ell'}$. Further, since $1 = (\det U) = \prod_{\ell} \det U_{\ell \ell'}$, we obtain that all $U_{\ell \ell'}$ are unimodular. This implies that $D^{-1} U D$ is unimodular. It remains to show that $(M_E B D)(D^{-1} U D)$ is $\Xi$-LLL-reduced. Let $R'$ and $R''$ respectively denote the R-factors of $(M_E B D)(D^{-1} U D)$ and $(M_E B D^{-1})(D^{-1} U D)$.

We have $r_{\ell j} = r_{\ell j}' r_{\ell j}''$ for all $i, j$. By $(\delta, \eta, \theta/2)$-reducibility of $(M_E B D^{-1})(D^{-1} U D)$, we have, for any $i < j$:

$$|r_{\ell j}''| = |r_{\ell j}'| r_{\ell j}'' \leq (\eta(2^{d_{\ell}}))^{-1} r_{\ell j}'' = (\eta(2^{d_{\ell}})^{-1}) r_{\ell j}'' \leq \frac{\eta}{2} r_{\ell j}''$$

$(1)$

If $i$ and $j$ belong to the same $I_{\ell'}$, then $d_i = d_j$ and the size-reducing condition of Definition 4 is satisfied. Otherwise, we have $i \in I_{\ell'}$ and $j \in I_{\ell''}$ for some $\ell < \ell'$. Thanks to the assumption on the LLL-reducing algorithm (and noting that the R-factor of $M_E B D^{-1}$ is $RD^{-1}$), we have:

$$r_{\ell j}' \geq \min_{i \in I_{\ell'}} r_{\ell i} \geq \min_{i \in I_{\ell'}} (\eta(2^{d_{\ell}})^{-1}) \geq \frac{\eta}{2} \max_{i \in I_{\ell'}} r_{\ell i} \geq \frac{\eta}{2} r_{\ell i}$$

For the second inequality, we used the fact that for a well-behaved LLL-reduction algorithm, the minimum of the R-factor diagonal factors in a block cannot decrease. Similarly, in the fourth inequality, we used the fact that the maximum of the R-factor diagonal factors in a block cannot increase. For the third inequality, we used the definition of the blocks and the lower bound on the gap between two blocks, and Lemma 14. As a result, we have $r_{\ell j}' \geq \frac{\eta}{2} r_{\ell i}$. By orthogonality, the distortion $\Sigma$ acts orthogonally to $r_{\ell i}$, with $\eta \geq \eta_{\ell i}$.

Similarly, by reducibility of $(M_E B D^{-1})(D^{-1} U D)$, we have:

$$\forall i : \delta(r_{\ell i}^*') = 2^{\delta d_{\ell}} (r_{\ell i}^*') \leq 2^{\delta d_{\ell}} \left( (r_{\ell i+1}^*')^2 + (r_{\ell i+1+1}^*')^2 \right) \leq 2^{\delta(d_{\ell'}-d_{\ell}+1)} (r_{\ell i+1}^*)^2 + (r_{\ell i+1+1}^*)^2) \leq (r_{\ell i+1}^*')^2 + (r_{\ell i+1+1}^*)^2$$

where we used the fact that $d_{\ell'} \geq d_i$. The output basis satisfies the Lovász’ conditions of Definition 6 This completes the proof of the theorem.

**5.2 Complexity analysis**

So far, we have shown that Algorithm 2 is correct. We now turn to estimating its run-time. Unless the exponents in $E_B$ are uncommonly huge, the dominating component of the cost is the LLL-reduction of Step 9. Our aim here is to bound the bit-size of the coefficients of the matrix $M_E B D^{-1}$, when this matrix is viewed as an integer matrix. The algorithm takes any floating-point lattice basis as input, but the run-time bound will depend on how close is $M_E B D^{-1}$ is to be LLL-reduced. More precisely, we consider a non-singular matrix $\Sigma$ and a set $\Xi$ of valid LLL-parameters such that $\Sigma^{-1} M_E B D$ is $\Xi$-LLL-reduced. Such a $\Sigma$ always exists (take $\Sigma$ such that $\Sigma^{-1} M_E B D$ is orthonormal), but the bit-size bound to be proven will depend on the singular values of $\Sigma$. More precisely, for any $\ell$, we define $E_{\ell}$ as the $[\ell]$-dimensional subvector space of $\mathbb{R}^m$ that is spanned by the columns of $M_E B D$ with indices in $I_{\ell}$. We define $F_{\ell}$ as the projection of $E_{\ell}$ orthogonally to $F_{\ell-1}$, and so forth, so that the column span of $M_E B D$ is the orthogonal sum of the $F_{\ell}$’s. Now, by orthogonality, the distortion $\Sigma$ acts independently on any of the $F_{\ell}$’s. We let $\Sigma_\ell$ denote the corresponding $|I_\ell|$-dimensional non-singular linear map. The bit-size bound of the integer matrix $M_E B D^{-1}$ is to be given as input to an LLL-reduction algorithm at Step 9 will involve the quantity $\log \prod_{\ell} \kappa(\Sigma_{\ell})$. By orthogonality of the $F_{\ell}$’s, the latter is bounded from above by $\log \prod_{1 \leq \ell \leq |\ell|} \kappa(\Sigma_{\ell})$, where $\sigma_1 \geq \ldots \geq \sigma_m$ are the singular values of $\Sigma$. The following lemma provides a bound on the amplitude of the $r_{\ell i}$’s within a block.

**Lemma 16.** With $\alpha'$ as in Lemma 4 (for $\Xi$), for any $\ell$, we have:

$$\max_{1 \leq \ell \leq |\ell|} \frac{1}{\kappa(\Sigma_{\ell})} \leq 3(8\alpha'/\theta)^{1/|\ell|} \kappa(\Sigma_{\ell})$$

**Proof.** We prove that for any $i, j \in I_{\ell}$, we have $r_{\ell j}/r_{\ell i} \leq 3(8\alpha'/\theta)^{1/|\ell|} \kappa(\Sigma_{\ell})$. Suppose first that $j \leq i$. Then, by Lemma 4 we have $r_{\ell j}/r_{\ell i} \leq (\alpha'/\theta)^{1/2}$, where $R'$ denote the R-factor of $C$. By Lemma 3 we obtain that $r_{\ell j}/r_{\ell i} \leq (\alpha'/\theta)^{1/2} \kappa(\Sigma_{\ell})$. Now, by Lemma 14 we obtain that $r_{\ell j}/r_{\ell i} \leq (\alpha'/\theta)^{1/2} \kappa(\Sigma_{\ell})$. Suppose now that $j > i$. If $r_{\ell i} = \max_{|I_{\ell}|} r_{\ell i}$, then the bound holds since the right hand side is $\geq 1$. Otherwise, from the definition of blocks, there exists some $i' \in I_{\ell}$ with $i < i'$ such that $r_{\ell i'} \leq (8\alpha'/\theta) \cdot r_{\ell i}$. Applying the same idea to $i'$ we get $r_{\ell i'}/r_{\ell i} \leq (8\alpha'/\theta) \cdot r_{\ell i}$, with $i' = i_{\ell-1}+1$, where $i_{\ell-1}$ is the number of times this recursion is applied. Since $j > i'$, we conclude that $r_{\ell j} \leq 3(8\alpha'/\theta)^{1/2} \kappa(\Sigma_{\ell}) r_{\ell i}/r_{\ell i}$ (using the first part of the proof).

From here, we can derive a bound on the amplitude of the diagonal coefficients of the R-factor of $M_E B D^{-1}$.
Lemma 17. Let $R'$ denote the R-factor of $MBEBD^{-1}$. Then \[ \frac{\max(r'_{i,j})}{\min(r'_{i,j})} \leq c_0 \cdot \prod_{\ell} \kappa(\Sigma_{\ell}) \] for some $c_0$ depending only on $\Sigma$.

Proof. Thanks to Lemma 15, we have that for all $\ell$, \[ \min_{i \in I_{\ell}} r'_{i,j} \leq 32 \cdot \max_{i \in I_{\ell}} r'_{i,j}. \] Using Lemma 8, we then translate the bound of Lemma 16 for $I_{\ell}$, in terms of the $r'_{i,j}$'s rather than the $r_{i,j}$'s, hence get: \[ \min_{i \in I_{\ell}} r'_{i,j} \leq 100(8^{\alpha/\gamma})^{|\ell|/\kappa(\Sigma)} \cdot \min_{i \in I_{\ell}} r_{i,j}. \] Taking the product over all values of $\ell$ leads to the result.

We can now prove the following bit-size bound for the input to the LLL-reduction algorithm.

Theorem 3. Assume that the input matrix $MB$ is integrable with \[ ||MB|| \leq 2^n. \] Let $\Sigma \in \mathbb{R}^{m \times m}$ be non-singular, such that $\Sigma^{-1}MBEB$ is \$\Sigma$-LLL-reduced, for some valid set $\Xi$ of LLL-parameters. Let $C = MBEBD^{-1}$ be the matrix given as input to an LLL-reduction algorithm at Step 9 of Algorithm 8. Then there exists a constant $c$ such that $C \in 2^{-k} \mathbb{Z}^{n \times m}$, for some $k$ satisfying:

\[ \log ||C|| - k \leq c \cdot n + 2p + 2 \log \prod_{1 \leq i \leq n/2} \frac{\sigma_i}{m^{i-1}}, \]

where $\sigma_1 \geq \ldots \geq \sigma_m$ denote the singular values of $\Sigma$.

Proof. Lemma 17 gives: \[ \max ||c_i|| \leq \text{cond}(C) \max r'_{i,j}, \] where $R'$ denotes the R-factor of $C$. Further, by Lemmata 7 and 9, there exists a constant $c_1$ such that $\text{cond}(C) \leq \kappa(\Sigma) \cdot c_1$. Using Lemma 17 and the fact that $\min ||c_i|| \geq \min r_{i,j}$, we obtain that

\[ \frac{\max ||c_i||}{\min ||c_i||} \leq c_0 \cdot \kappa(\Sigma) \cdot \prod_{1 \leq i \leq n/2} \frac{\sigma_i}{m^{i-1}}, \]

for some constant $c_2$. Now, using the assumption that $MB$ is integral of norm $\leq 2^n$, we have

\[ \frac{\max ||c_i||}{\min ||c_i||} \leq 2^n \cdot \frac{\max ||c_i||}{\min ||c_i||} \leq 2^n c_2 \cdot \prod_{1 \leq i \leq n/2} \frac{\sigma_i}{m^{i-1}}. \]

To complete the proof, we note that the entries of $C$ are sums of powers of 2, and we use that $2^n \cdot \frac{\max ||c_i||}{\min ||c_i||}$ bounds from above the ratio between the smallest and the largest entries.

As our bound applies to any $\Sigma$ such that $\Sigma^{-1}MBEB$ is LLL-reduced, we are interested in the existence of such a $\Sigma$ with a small log $\Pi_{1 \leq i \leq n/2} \frac{\sigma_i}{m^{i-1}}$.

6. PRACTICAL CONSIDERATIONS

Several important points deserve further investigations, especially from a practical point of view. The sharpness of the sufficient bound $2 \log \text{cond}(R) + n(1 + c) + O(\log m)$ on the input precision is unclear. Studying heuristic values for the different quantities to choose, e.g. for the constant $c$ of Lemma 13 remains to be done. In the same vein, understanding the impact of the chosen precision and the input basis structure on the output parameters $\Xi = (\delta, \eta, \theta)$ is an interesting problem. For an idea of practical accelerations that can be obtained thanks to the scaling, we may refer to [8] Se. 5. A extensive experimental study should be made.

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7. REFERENCES


