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On the complexity of the Arora-Ge Algorithm  
against LWE

**Martin R. Albrecht, Carlos Cid, Jean-Charles  
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**Abstract**

Arora & Ge [5] recently showed that solving LWE can be reduced to solve a high-degree non-linear system of equations. They used a linearization to solve the systems. We investigate here the possibility of using Gröbner bases to improve Arora & Ge approach.

**Introduction**

The Learning With Errors (LWE) Problem was introduced by Regev in [27, 26]. It is a generalisation for large primes of the well-known LPN (Learning Parity with Noise) problem. Since its introduction, LWE has become a source of many innovative cryptosystems, such as the oblivious transfer protocol by Peikert et al. [25], a cryptosystem by Akavia et al. [1] that is secure even if almost the entire secret key is leaked, homomorphic encryption [21, 10, 4], etc. . . Reasons of LWE’s success in cryptography include its simplicity as well as convincing theoretical arguments regarding its hardness, i.e. a reduction from (worst-case) assumed hard lattice problems to (average-case) LWE.

The purpose of this paper is to investigate whether algebraic techniques (e.g. [16, 17, 18, 19, 3, 2, 20]) can be used in the context of LWE. This is motivated by a recent result Arora & Ge [5] who showed that solving LWE can be reduced to solve a high-degree non-linear system of equations.

**Learning With Errors**

We reproduce below the definition of the LWE problem from [27, 26].

**Definition 1** (LWE). *Let  $n \geq 1$  be the number of variables,  $q$  be an odd prime integer,  $\chi$  be a probability distribution on  $\mathbb{Z}_q$  and  $\mathbf{s}$  be a secret vector in  $\mathbb{Z}_q^n$ . We denote by  $L_{\mathbf{s},\chi}^{(n)}$  the probability distribution on  $\mathbb{Z}_q^n \times \mathbb{Z}_q$  obtained by choosing  $\mathbf{a} \in \mathbb{Z}_q^n$  at random, choosing  $e \in \mathbb{Z}_q$  according to  $\chi$ , and returning  $(\mathbf{a}, c) = (\mathbf{a}, \langle \mathbf{a}, \mathbf{s} \rangle + e) \in \mathbb{Z}_q^n \times \mathbb{Z}_q$ . LWE is the problem of finding  $\mathbf{s} \in \mathbb{Z}_q^n$  given pairs  $\mathbb{Z}_q^n \times \mathbb{Z}_q$  sampled according to  $L_{\mathbf{s},\chi}^{(n)}$ .*

The modulus  $q$  is typically taken to be polynomial in  $n$ , and  $\chi$  is the discrete Gaussian distribution on  $\mathbb{Z}_q$  with mean 0 and standard deviation  $\sigma = \alpha \cdot q$ , for some  $\alpha$ . To discretize the Gaussian distribution  $\mathbb{N}0, \sigma^2$  modulo  $q$ , we sample according to  $\mathbb{N}0, \sigma^2$  and round to the nearest integer mod  $q$ . In what follows,  $\chi_{\alpha,q}$  will then denote this discretized distribution.

A typical setting for the standard deviation (std) is  $\sigma = n^\epsilon$ , with  $\epsilon, 0 \leq \epsilon \leq 1$ . For example, [27] suggests  $q \approx n^2$  and  $\alpha = 1/(\sqrt{n} \cdot \log^2 n)$ . Indeed, as soon as  $\epsilon \geq 1/2$  (worst-case) GAPSVP  $-\tilde{O}(n/\alpha)$  reduces to (average-case) LWE<sup>1</sup>. Thus, any algorithm solving LWE (when  $\epsilon \geq 1/2$ ) can be used for GAPSVP  $-\tilde{O}(n/\alpha)$ . We emphasize that it is widely believed that only exponential algorithm exists for solving GAPSVP  $-\tilde{O}(n/\alpha)$ .

Recently, Arora & Ge [5] introduced a variant of LWE with *structured* errors. In this setting, you have given an oracle such that given LWE samples returns polynomials which vanish on the errors.

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<sup>1</sup>The reduction is quantum if  $q$  is polynomial but can be made [24] classical if  $q$  is super polynomial.

They showed that the (discretized) Gaussian intrinsically induced a structure on the errors. This feature can be used to reduce LWE to the problem of solving a non-linear system of multivariate equations.

The total complexity (time and space) of their approach is  $2^{\tilde{O}(n^{2\varepsilon})}$ . It is then subexponential when  $\varepsilon < 1/2$ , but remains exponential when  $\varepsilon \geq 1/2$ . It is interesting that Arora&Ge reach with a completely different approach the  $\varepsilon = 1/2$  hardness limit advised by Regev [27, 26].

Note that an improvement on Arora&Ge could allow to challenge the ‘subexponentiality’ of GAPSVP –  $\tilde{O}(n/\alpha)$ . Remark that [5] uses linearization to solve the non-linear system. It is then natural to investigate whether more advanced tools, such as Gröbner bases [11, 12, 13], could improve the algorithm of Arora&Ge.

In this note, we will show that Gröbner bases can bring a practical improvement on the complexity of [5]. We also briefly discuss whether Gröbner bases can (or can not) allow to change the complexity class of Arora&Ge. Before that, we need to recall some basic complexity results about Gröbner bases.

### Gröbner bases – Complexity Results

Gröbner basis is probably the main tool allowing to solve non-linear system of finite fields. From an algorithmic point of view, Lazard [22] showed that computing the Gröbner basis for a system of polynomials is equivalent to perform a Gaussian elimination on the *Macaulay matrices* [23]  $\mathcal{M}_{d,m}^{\text{acaulay}}$  for  $d, 1 \leq d \leq D$  for some integer  $D$ . Moreover, the most efficient known algorithms such as  $F_5$  [15] reduce Gröbner basis computations to a series of Gaussian eliminations on matrices of increasing sizes.

**Definition 2** (Macaulay Matrix [23]). *Let  $f_1, \dots, f_m \in \mathbb{Z}_q[x_1, \dots, x_n]$ . The Macaulay matrix  $\mathcal{M}_{d,m}^{\text{acaulay}}(f_1, \dots, f_m)$  of degree  $d$  is defined as follows: list “horizontally” all the degree  $d$  monomials from smallest to largest sorted by some fixed admissible monomial ordering. The smallest monomial comes last. Multiply each  $f_i$  by all monomials  $t_{i,j}$  of degree  $d - d_i$  where  $d_i = \deg(f_i)$ . Finally, construct the coefficient matrix for the resulting system:*

$$\mathcal{M}_{d,m}^{\text{acaulay}}(f_1, \dots, f_m) := \begin{matrix} & \text{monomials of degree } \leq d \text{ sorted for } < \\ \begin{pmatrix} (t_{1,1}, f_1) \\ (t_{1,2}, f_1) \\ \vdots \\ (t_{m,1}, f_m) \\ (t_{m,2}, f_m) \\ \vdots \end{pmatrix} & \begin{pmatrix} \\ \\ \\ \\ \\ \end{pmatrix} \end{matrix}$$

**Theorem 3** ([22]). *Let  $\mathbf{f} = (f_1, \dots, f_m) \in (\mathbb{Z}_q[x_1, \dots, x_n])^m$  and  $<$  be a monomial ordering. There exists a positive integer  $D$  for which Gaussian elimination on all  $\mathcal{M}_{d,m}^{\text{acaulay}} = (f_1, \dots, f_m)$  matrices for  $d, 1 \leq d \leq D$  computes a Gröbner basis of  $\langle f_1, \dots, f_m \rangle$  w.r.t. to  $<$ . The degree  $D$  will be called degree of regularity of  $f_1, \dots, f_m$ .*

Consequently, the complexity of computing a Gröbner basis is bounded by the complexity of performing Gaussian elimination on the Macaulay matrix in some degree  $D$ . Roughly, the complexity of computing a Gröbner basis with an algorithm based on the degree of regularity (such as – but not limited too – Buchberger’s algorithm,  $F_4, F_5$  [15, 11, 12, 14]) is:

$$o\left(\binom{n+D}{D}^\omega\right), \quad (1)$$

where  $2 \leq \omega < 3$  is the linear algebra constant, and  $D$  is the degree of semi-regularity of the system.

In general, computing the degree of regularity of a system is a difficult problem. However, it is known for a specific family of polynomial systems [6, 8, 7, 9].

**Definition 4** (Semi-regular Sequence [8]). *Let  $m > n$ , and  $f_1, \dots, f_m \in \mathbb{Z}_q[x_1, \dots, x_n]$  be homogeneous polynomials of degrees  $d_1, \dots, d_m$  respectively and  $I$  the ideal generated by these polynomials. The system is said to be a semi-regular sequence if the Hilbert series [13] of  $I$  w.r.t. the grevlex order is:*

$$H_I(z) = \left[ \frac{\prod_{i=1}^m (1 - z^{d_i})}{(1 - z)^n} \right]_+, \quad (2)$$

where  $[S]_+$  denotes the series obtained by truncating  $S$  before the index of its first non-positive coefficient. Thus, the degree of regularity  $D$  involved in Theorem 3 for a semi-regular sequence is:

$$1 + \deg(H_I).$$

## Improving Arora-Ge Approach

We briefly detail below the linearization approach of Arora-Ge. We then discuss whether Gröbner bases can be used in this context.

### Basic Arora-Ge Algorithm – A Linearization Approach

The idea of [5] is to generate a non-linear noise-free system of equations from LWE samples. This is due to the following well-known feature of a Gaussian noise:

**Lemma 5.** *Let  $C > 0$  be a constant. It holds that:*

$$\Pr[e \stackrel{\$}{\leftarrow} \chi_{\alpha, q} : |e| > C \cdot \sigma] \leq e^{o(-C^2)}.$$

As a consequence, elements sampled from a Gaussian distribution only takes values on a (small) subset  $[-C \cdot \sigma, \dots, C \cdot \sigma]$  of  $\mathbb{Z}_q$  with high probability. From now on, we set  $t = C \cdot \sigma$ . We can re-interpret Lemma 5 algebraically by considering the polynomial:

$$P(X) = X \prod_{i=1}^t (X + i)(X - i).$$

Clearly  $P$  is of degree  $2t + 1 \in o(\sigma)$ . Thus, if  $e \stackrel{\$}{\leftarrow} \chi_{\alpha, q}$ , then  $P(e) = 0$  with probability at least  $1 - e^{o(-C^2)}$ .

For  $i \geq 1$ , let  $(\mathbf{a}_i, \langle \mathbf{a}_i, s \rangle + e_i) = (\mathbf{a}_i, b_i) \in \mathbb{Z}_q^n \times \mathbb{Z}_q$ . If  $e_i \stackrel{\$}{\leftarrow} \chi_{\alpha, q}$ , then

$$P(\mathbf{a}_i, \langle \mathbf{a}_i, s \rangle - b_i) = 0, \quad (3)$$

with probability at least  $1 - e^{o(-C^2)}$ . As a consequence, each sample  $(\mathbf{a}_i, \langle \mathbf{a}_i, s \rangle + e_i) = (\mathbf{a}_i, b_i) \in \mathbb{Z}_q^n \times \mathbb{Z}_q$  allows to generate a non-linear equation of degree  $2t + 1$  in the  $n$  components of the secret  $\mathbf{s}$ .

The idea of Arora & Ge is then to generate sufficiently many equations as in (3) to perform a linearization. However, one has to choose the constant – denoted by  $C_{AG}$  – occurring in Lemma 5 sufficiently big so that all errors generated lies with high probability in  $[-C_{AG} \cdot \sigma, \dots, C_{AG} \cdot \sigma] \subseteq \mathbb{Z}_q$ , i.e. the secret  $\mathbf{s}$  is indeed a common solution of the  $M_{AG}$  equations constructed as in (3). To this end, we set:

$$p_f = \frac{M_{AG}}{e^{o(C_{AG}^2)}}.$$

This is the probably that the secret  $s \in \mathbb{Z}_q^n$  is not solution of the system  $\mathcal{S}_{AG}$  generated from  $M_{AG}$  equations as in (3), i.e. the probability of failure of Arora-Ge approach. Let also  $D_{AG} = 2C_{AG} \cdot \sigma + 1$  be the degree of the equations occurring in  $\mathcal{S}_{AG}$ . According to [5], taking  $C_{AG} \in \tilde{o}(\sigma)$  allows to make the probability of failure negligible.

To summarize, Arora-Ge approach reduces to linearize at system of  $M_{AG}$  equations of degree  $D_{AG} = 2C_{AG} \cdot \sigma + 1 \in \tilde{o}(\sigma^2)$ . Moreover, correctness of this approach can be proven:

**Theorem 6.** [5] Let  $D_{AG} < q$ . The system obtained by linearizing  $M_{AG} = O\left(q \cdot \log(q) \binom{n+D_{AG}}{D_{AG}} \sigma\right) = n^{O(D_{AG})} = 2^{\tilde{O}(D_{AG})}$  equations as in (3) has at most one solution with high probability.

The time complexity of the basic Arora-Ge approach is then

$$C_{AG}^{\text{plx}} = n^{O(D_{AG})} = 2^{\tilde{O}(\sigma^2)} = 2^{\tilde{O}(n^{2\varepsilon})}.$$

Note also this algorithm also requires  $2^{\tilde{O}(n^{2\varepsilon})}$  LWE samples for performing the linearization.

### From Linearization to Gröbner Bases

The question we try to address here is whether the complexity  $C_{AG}^{\text{plx}}$  can be improved by using Gröbner bases instead of linearization. The rationale is that you can decrease the constant  $C_{AG}$  (and so the degree of the equations) to a value smaller than  $\tilde{O}(n^{2\varepsilon})$  by considering less equations (whilst keeping the probability  $p_f$  of failure similar in both approaches). However, the cost of the solving step increases since one has to compute a Gröbner basis. The question is then to find – if any – a tradeoff allowing to improve upon linearization.

To do so, we will consider a number of equations of the form  $\sqrt[\theta]{M_{AG}}$ , with  $\theta > 1$  ( $\theta = 1$  is the basic Arora-Ge). We want to keep the probability of failure similar for the linearization and Gröbner basis approaches. As a consequence, we need to take a constant  $C_\theta$  such that:

$$p_f = \frac{\sqrt[\theta]{M_{AG}}}{e^{O(C_\theta^\theta)}}.$$

An easy calculation leads to  $C_\theta \in \tilde{O}\left(\frac{C_{AG}}{\sqrt{\theta}}\right)$ . Thus, decreasing the number of equations from  $M_{AG}$  to  $\sqrt[\theta]{M_{AG}}$  allows to divide the constant  $C_{AG}$  by a factor  $\sqrt{\theta}$ . The degree of the equations we are doing to consider is then equal to  $2\sigma \cdot C_\theta + 1 \in \tilde{O}\left(\frac{\sigma^2}{\sqrt{\theta}}\right)$ .

The question is now to find a good candidate for  $\theta$ . Typically, if  $\theta$  is too big then you will greatly decrease the number of equations, but the cost of the solving step will become prohibitive and the total complexity will be worse than for a linearization.

We have considered a  $\theta$  of the form:  $\theta = n^{2\beta}$ , for some  $\beta \geq 0$  (note that we get the basic Arora-Ge by taking  $\beta = 0$ ). In this new setting, we get a constant  $C_\beta = n^{\varepsilon-\beta}$ . We have then to solve a system having  $M_\beta = \sqrt[n^{2\beta}]{M_{AG}} \in 2^{\tilde{O}(n^{2(\varepsilon-\beta)})}$  equations of degree  $D_\beta = \tilde{O}(n^{2\varepsilon-\beta})$ . We denote such a system by  $S_{GB}(\beta)$ .

The question is to determine the complexity  $C_{GB-AG}^{\text{plx}}(\beta)$  of solving  $S_{AG}(\beta)$ . This reduces to studying its degree of regularity  $D_{reg}^\beta$ . Given current algorithms, the specific structure of the system does not allow to solve it faster than random systems. As a consequence, we assume that  $D_{reg}^\beta$  is not bigger than the degree of regularity of a semi-regular system of the same size<sup>2</sup>, namely:

$$D_{reg}^\beta \leq 1 + \deg(H_\beta),$$

where:

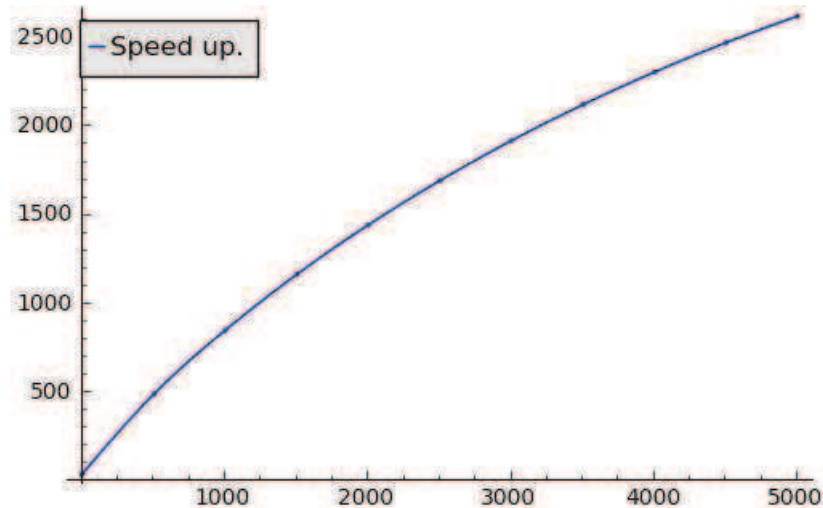
$$H_\beta(z) = \left[ \frac{(1-z^{D_\beta})^{M_\beta}}{(1-z)^n} \right]_+,$$

where  $[\cdot]_+$  denotes the series obtained by truncating before the index of its first non-positive coefficient.

We present below some experiments performed for  $\beta = 1/5$ . We have computed explicitly the complexities for both approaches: linearization and Gröbner bases. As suggested in [27],

<sup>2</sup>We have performed few experiments for small parameters. The experiments seem to confirm this hypothesis.

we considered  $q \approx n^2$  and  $\alpha = 1/(\sqrt{n} \cdot \log^2 n)$ . We plotted below the speed-up we obtained, i.e.  $\log_2 \left( \frac{C_{GB-AG}^{plx}(\beta)}{C_{AG}^{plx}} \right)$  (y-axis) for  $n, 0 \leq n \leq 5000$ . We can see that Gröbner bases allow to improve the complexity of the basic Arora-Ge when  $n \leq 5000$  (x-axis). Note that further experiments are required to confirm this behavior when  $n$  tends to infinity<sup>3</sup>



However, the form of the speed-up also tends to suggest that we only improve from a constant  $C_{AG}^{plx}$ . change the asymptotical behavior of the Arora&Ge approach. we mention that we are currently considering several forms for the  $\beta$ . In particular,  $\beta$  which is not a constant but a function of  $n$ . As a conclusion, we also emphasize that Arora-Ge needs exponential (or subexponential) number of LWE samples. For most cryptosystems based on LWE, you have access to much less samples, typically polynomially-many. In this situation, you have then not enough samples to perform the linearization and the only option to mount the Arora&Ge approach is to solve the system by using Gröbner bases.

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<sup>3</sup>Note that the degree of the equations involved being huge, it becomes rather costly to just expand the Hilbert series for the systems considered.

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