

PROBABILISTIC SOLUTIONS OF EQUATIONS IN THE BRAID GROUP

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ABSTRACT. Given a system of equations in a “random” finitely generated subgroup of the braid group, we show how to find a small ordered list of elements in the subgroup, which contains a solution to the equations with a significant probability. Moreover, with a significant probability, the solution will be the first in the list. This gives a probabilistic solution to: The conjugacy problem, the group membership problem, the shortest presentation of an element, and other combinatorial group-theoretic problems in random subgroups of the braid group.

We use a memory-based extension of the standard length-based approach, which in principle can be applied to any group admitting an efficient, reasonably behaving length function.

1. THE GENERAL METHOD

1.1. Systems of equations in a group. Fix a group G . A *pure equation* in G with variables X_i , $i \in \mathbb{N}$, is an expression of the form

$$(1) \quad X_{k_1}^{\sigma_1} X_{k_2}^{\sigma_2} \dots X_{k_n}^{\sigma_n} = b,$$

where $k_1, \dots, k_n \in \mathbb{N}$, $\sigma_1, \dots, \sigma_n \in \{1, -1\}$, and b is given. A *parametric equation* is one obtained from a pure equation by substituting some of the variables with given (known) parameters. By *equation* we mean either a pure or a parametric one. Since any probabilistic method to solve a system of equations implies a probabilistic mean to check that a given system has a solution, we will confine attention to systems of equations which possess a solution.

Given a system of equations of the form (1), it is often possible to use algebraic manipulations (taking inverses and multiplications of equations) in order to derive from it a (possibly smaller) system of

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equations all of which share the same leading variable, that is, such that all equations have the form

$$(2) \quad XW_i = b_i,$$

where X is one of the variables appearing in the original system. The task is to find the leading variable X in the system (2). Having achieved this, the process can be iterated to recover all variables appearing in the original system (1). In the sequel we confine our attention to systems consisting of one or more equations of the form (2).

1.2. Solving equations in a finitely generated group. The following general scheme is an extension of one suggested by Hughes and Tannenbaum [6] and examined in [2]. Our new scheme turns out dramatically more successful (compare the results of Section 2 to those in [2]).

It is convenient to think of each of the variables as an unknown element of the group G . Assume that the group G is generated by the elements a_1, \dots, a_m , and that there exists a “reasonable” length function $\ell : G \rightarrow \mathbb{R}^+$, that is, such that the expected length tends to increase with the number of multiplied generators.

Assume that equations of the form (2), $i = 1, \dots, k$, are given. We propose the following algorithm: Since $X \in G$, it has a (shortest) form

$$X = a_{j_1}^{\sigma_1} a_{j_2}^{\sigma_2} \dots a_{j_n}^{\sigma_n}.$$

The algorithm generates an ordered list of M sequences of length n , such that with a significant probability, the sequence

$$((j_1, \sigma_1), (j_2, \sigma_2), \dots, (j_n, \sigma_n))$$

(which codes X) appears in the list, and tends to be its *first* member. The algorithm works with memory close to $M \cdot n$, thus M is usually chosen according to the memory limitations of the computer (see also Remark 1.4).

Step 1: For each $j = 1, \dots, m$ and $\sigma \in \{1, -1\}$, compute $a_j^{-\sigma} b_i = a_j^{-\sigma} XW_i$ for each $i = 1, \dots, k$, and give (j, σ) the score $\sum_{i=1}^k \ell(a_j^{-\sigma} b_i)$. Keep in memory the M elements (j, σ) with the least scores.

Step $s > 1$: For each sequence $((j_1, \sigma_1), \dots, (j_{s-1}, \sigma_{s-1}))$ out of the M sequences stored in the memory, each $j_s = 1, \dots, m$ and each $\sigma_s \in \{1, -1\}$, compute the sum of the lengths of the elements

$$a_{j_s}^{-\sigma_s} (a_{j_{s-1}}^{-\sigma_{s-1}} \dots a_{j_1}^{-\sigma_1} b_i) = a_{j_s}^{-\sigma_s} a_{j_{s-1}}^{-\sigma_{s-1}} \dots a_{j_1}^{-\sigma_1} XW_i,$$

over $i = 1, \dots, k$, and assign the resulting score to the sequence $((j_1, \sigma_1), \dots, (j_s, \sigma_s))$. Keep in memory only the M sequences with the least scores.

We still must describe the *halting* condition for the algorithm. If it is known that X can be written as a product of at most n generators, then the algorithm terminates after step n . Otherwise, the halting decision is more complicated. In the most general case we can decide to stop the process when the sum of the M scores increases rather than decreases. However, in many specific cases the halting decision can be made much more effective – see the examples below.

We describe several applications of the algorithm.

Example 1.1 (Parametric equations). If some of the words W_i in the equations (2) begin with a known parameter P_i , then the heuristic decision when to stop can be made much more effective: If at some step X was completely peeled of the equation, then we know the words W_i . To test this, for each of the M suggestions for X , we calculate the words W_i and check whether the sum of the lengths $\ell(P_i^{-1}W_i)$ is significantly smaller than that of the lengths $\ell(W_i)$. In fact, this allows us to determine, with significant probability, which of the M candidates for X is the correct one.

Example 1.2 (The Conjugacy Problem and its variants). The approach in Example 1.1 can also be applied in the case that the system of equations (2) consists of a *single* equation. This is the case, e.g., in the *parametric conjugacy problem*, where XPX^{-1} and P are given¹ and we wish to find X . Note that in this case the algorithm can be modified to become much more successful if at each step s we peel off the generator $a_{j_s}^{\sigma_s}$ from *both sides* of the element (more precisely, we peel off $a_{j_s}^{\sigma_s}$ from the left and $a_{j_s}^{-\sigma_s}$ from the right).

Observe, though, that if n is known in advance (as in many applications, e.g., [1, 7]), then in principle the original algorithm works, which means that we can solve the conjugacy problem *even if we do not know the conjugated element P* .

Example 1.3 (Group Membership and Shortest Presentation problems). Assume that G is a finitely generated subgroup of some larger group L . Given $g \in L$, we wish to decide whether $g \in G$. In this case we simply run our algorithm on g using the generators of G , and after each step check whether g is coded by one of our M sequences. This also provides (probabilistically) a way to write an element $g \in G$ as

¹In fact, it is not necessary to know P – see next paragraph.

a product of the generators of G , and with a significant probability it will be the shortest way to write it this way.

Remark 1.4 (Complexity). Note that the parameter M determining the length of the final list also affects the running time of the algorithm. As stated, if it runs n steps then it performs about

$$\sum_{s=1}^n kM(s+2m) = n(n+4m+1)kM/2$$

group multiplications and $2kmnM$ evaluations of the length function ℓ . (Recall that m denotes the number of the generators of the group, and k denotes the number of equations.) The running time can be improved at the cost of additional memory (e.g., one can keep in memory the M elements of the form $a_{j_{s-1}}^{-\sigma_{s-1}} \cdots a_{j_1}^{-\sigma_1} b_i$, which were computed at step $s-1$, to reduce the number of multiplications in step s). Note further that the algorithm is completely parallelable.

In the next section we give experimental evidence for this algorithm's ability to solve, with surprisingly significant probability, arbitrary equations in "random" finitely generated subgroups of the braid group B_N with nontrivial parameters.

2. EXPERIMENTAL RESULTS IN THE BRAID GROUP

In the following definition (only), we assume that the reader has some familiarity with the braid group B_N and its algorithms. Some references for these are [3, 7] and references therein.

The *Garside normal form* of an element w in the braid group B_N is a unique presentation of w in the form $\Delta_N^{-r} \cdot p_1 \cdots p_m$, where $r \geq 0$ is minimal and p_1, \dots, p_m are permutation braids in left canonical form. The following length function was introduced in [2], where it was shown that it exhibits much better properties than the usual length function associated with the Garside normal form.

Definition 2.1 ([2]). Let $w = \Delta_N^{-r} \cdot p_1 \cdots p_m$ be the Garside normal form of w . The *Reduced Garside length* of w is defined by

$$\ell_{\text{RG}}(w) = r \binom{N}{2} + \sum_{i=\min\{r,m\}+1}^m |p_i| - \sum_{i=1}^{\min\{r,m\}} |p_i|.$$

Our major experiment was made in subgroups of B_N with $N = 8$, which is large enough so that B_N is not trivial, but not too large so that we could perform a very large number of experiments. The finitely generated subgroups in which we worked were random in the sense that

each generator was chosen as a product of 10 randomly² chosen Artin generators.³ In this experiment we checked the effectiveness of our algorithm for the *parameters list* (m, n, k, l, M) , where:

- (1) m (the number of generators of the subgroup) was 2, 4, or 8,
- (2) n (the number of generators multiplied to obtain X) was 16, 32, or 64,
- (3) k (the number of given equations of the form (2)) was 1, 2, 4, or 8,
- (4) l (the number of generators multiplied to obtain the words W_i in the equations (2)) was 4 or 8; and
- (5) M (the available memory) was 2, 4, 8, 16, 32, 64, 128, 256, or 512.

(see Section 1.2). This makes a total of $3 \cdot 3 \cdot 4 \cdot 2 \cdot 9 = 648$ parameters lists, for each of which we repeated the experiment about 16 times.

X tends to be first. In about 83% of these experiments, X was a member in the resulting list of M candidates. A natural problem is: Assume that we increase M . Then experiments show that the probability of X appearing in the resulting list becomes larger,⁴ but now we have more candidates for X , which is undesired when we cannot check which member in the list is X . However, it turns out that even for large values of M , X tends to be among the first few in the list. In 71% of our experiments, X was actually the first in the list, and when $M = 512$, the probabilities for X ending in position $i = 1, 2, 3, \dots$ is decreasing with i , and the first few probabilities are: 0.83, 0.08, 0.03, and 0.01.

Group membership is often solved correctly. The experiments corresponding to the group membership problem are those with $k = 1$: In these cases we are given a single element XW and find a presentation of X using the given generators; this generalizes the case that we are given X and find its presentation, when it is possible (see Section 1.3). Checking the experiments with $k = 1$, $m = 4$ or 8, and $M = 512$, we get a success ratio of 0.98.

Logistic regression. In order to describe the dependence of the success ratio in the parameters involved, we are applying the methods of logistic regression. Let x_1, \dots, x_5 denote the logarithms to base 2 of the parameters m, n, k, l, M , respectively. Since the probability of success

²In this section, *random* always means with respect to the uniform distribution on the space in question. However, we believe that good results would be obtained for any nontrivial distribution.

³In this section, *generator* means a generator or its inverse.

⁴At first glance this seems a triviality, but observe that when M is increased, the correct answer has more competitors.

p in each case is a number between 0 and 1, a standard linear model (expressing p as a linear combination of the variables x_i) is not suitable. Instead, it is customary to express the function $L = \log(p/(1-p))$ as such a linear combination of the variables x_i (so that $p = e^L/(1+e^L)$). This is called the *logistic model*. Note that under this transformation the derivative of p with respect to L is $p(1-p)$, so an addition of ΔL to L will increase p to approximately $p + p(1-p)\Delta L$. The best approximation in this model is

$$(3) \quad L \approx 7.0814 - 1.7165x_1 - 0.7547x_2 + 0.1094x_3 + 0.5437x_5.$$

The quality of the approximation is measured by the variance of the error. Since we are taking the best linear approximation, adding *any* variable (even a random independent one) reduces the variance of the error. The significance level of a variable x_i roughly measures the probability that adding this variable to the others will have its reducing effect, assuming it was random. The typical threshold is 0.05: A significance level of 0.05 or below means that the variable has a significant contribution to the approximation L , which could not be attained by a variable independent of L . In the approximation (3), all variables have significance level < 0.0003 , except for the variable x_4 (corresponding to l) which has significance level 0.096, and is therefore not taken into consideration in the approximation (3).

We have verified that Approximation (3) gives a fairly good estimation of the success probabilities for the tried parameters.

Doubling the memory. Figure 1 shows the effect of doubling M on the success probability, according to Approximation (3). To create this figure, we fixed $m = 8$ and $k = 1$, and for each $M = 2^1, 2^2, \dots, 2^{10}$ we have drawn the graph of the success probability p with respect to $\log_2(n)$.

Remark 2.2. According to Approximation (3), in order to maintain the success probability when m is doubled, M should be multiplied by $2^{1.7165/0.5437} \approx 8.92$.

Another interpretation is as follows. Assume that we wish to decide what should the value of M be to get success probability 0.5, that is, $L = 0$. From (3) it follows that

$$x_5 \approx (-7.0814 + 1.7165x_1 + 0.7547x_2 - 0.1094x_3)/0.5437$$

and therefore

$$M = 2^{x_5} \approx 0.00012 \cdot m^{3.16} \cdot n^{1.39}/k^{0.2}.$$

It seems that the prediction capabilities of Approximation (3) for larger parameters are not bad.

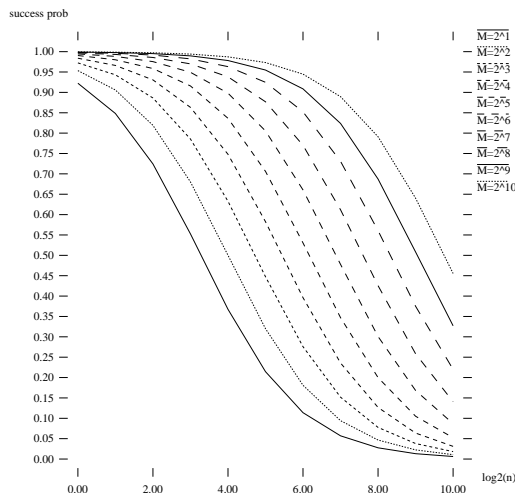


FIGURE 1. The effect of doubling M on the success probability

Example 2.3. Using Approximation (3), the predicted success probability for parameters list $(16, 128, 8, 8, 1024)$ is 0.668. An experiment for these parameters succeeded in 9 out of 11 tries (about 0.82).

2.1. Identifying failures. Figure 2 describes the position of the correct prefix of X and the average score of all M sequences in the memory during the steps of the algorithm (The graphs are normalized for graphical clarity). Two typical examples are given, both for parameters list $(2, 64, 8, 8, 128)$. An interesting observation is that when the correct prefix is not among the first few, the average length decreases more slowly with the steps of the algorithms.

It turns out that in most of the cases where the correct prefix of X does not survive a certain step (that is, it is not ranked among the first M sequences), the average length after several more steps almost does not decrease. Figure 3 illustrates two typical cases, with parameters list $(2, 64, 8, 8, 16)$ (left) and $(2, 64, 8, 8, 8)$ (right).

This allows us to identify failures within several steps after their occurrence. In such cases one approach is to return a few steps backwards, increase M for the next (problematic) few steps, and then decrease it again.

We must stress that these are only typical cases, and several pathological cases (where the correlation between the decrease in the lengths and the position of the correct prefix was not as expected) were also encountered. In these rare cases, we observed at least one of the following phenomena: Either the generators a_i could be written as a product of

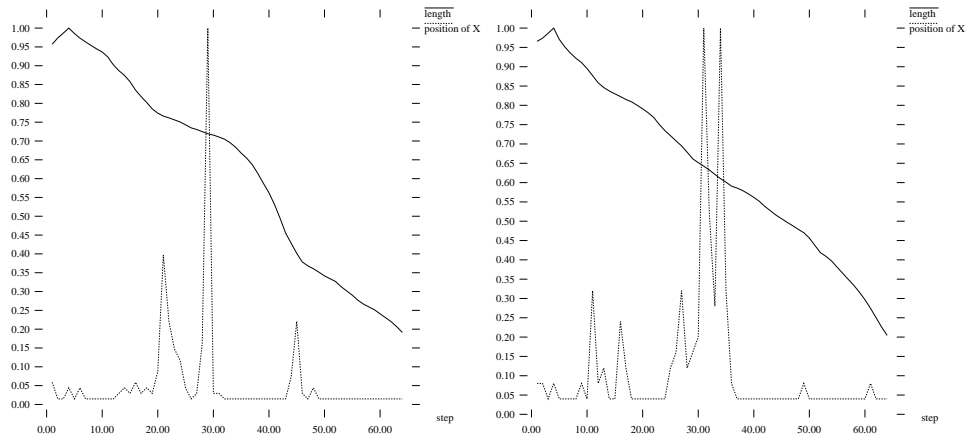


FIGURE 2. Position of the correct prefix in successful runs

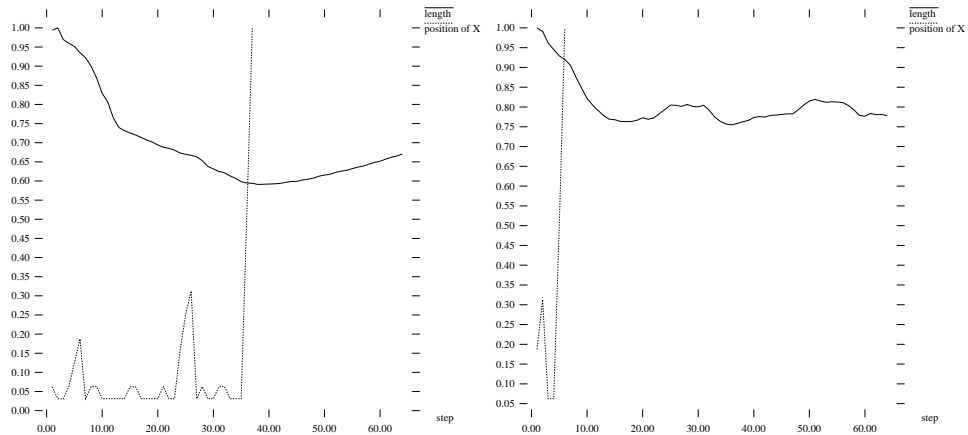


FIGURE 3. Position of the correct prefix in unsuccessful runs

very few Artin generators, due to several cancellations in the product defining them (recall that each generator a_i is a product of 10 random Artin generators in B_8), or else some (but not all) of the Artin generators multiplied to obtain a_i were cancelled when multiplied with some of the Artin generators defining a_j (or its inverse), so that the resulting element x could be written using much fewer Artin generators than expected. This violates the required monotonicity of the length function and makes the algorithm fail.

2.2. Working in B_N when N is larger. For the parameters lists $(2, 16, 8, 8, 2)$ and $(8, 16, 8, 8, 128)$, we have checked the success probabilities for $N = 8, 10, 12, 14, 16, 20, 24, 28, 32, 36, 40, 50, 60, 70, 80, 96,$ and 100 . The results are shown in Figure 4. While the success probability decreases with N , it does not become as negligible as one might expect. Moreover, it can be significantly enlarged at the cost of increasing M .

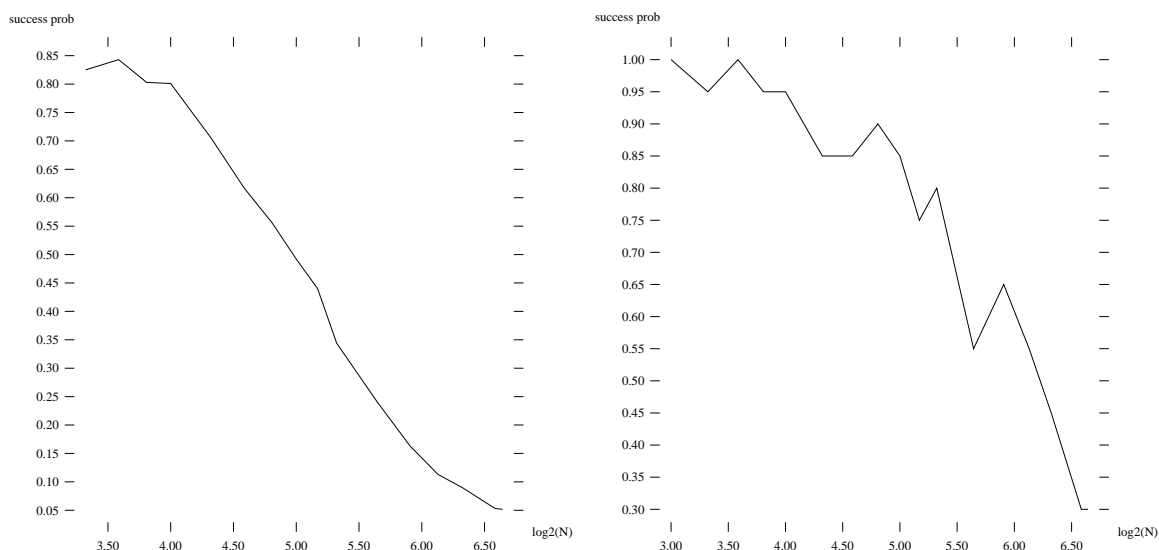


FIGURE 4. Success probability for $(2, 16, 8, 8, 2)$ (left) and for $(8, 16, 8, 8, 128)$ (right)

3. CONCLUDING REMARKS

Our results suggest that whenever G is a finitely generated subgroup of the braid group, which is obtained by a sufficiently “random” process, and the involved parameters are feasible for handling the group elements in the computer, it is possible to solve equations in the given group with significant success probabilities. This significantly extends similar results concerning the conjugacy problem (with known parameters) obtained in other works (e.g., [5]).

This approach seems to imply the vulnerability of the key exchange protocols suggested in [1, 7], since their security is based on the difficulty of the Conjugacy Problem in “random” subgroups of the braid group (see Example 1.2). It should be stressed that our experiments were performed with a small amount of memory (parameter M), which could, in feasible settings, be increased by several orders of magnitude

and therefore significantly improve the success probability. Since even a small non-negligible success probability in attacking the protocol implies that it is not secure, it seems that in order to immune the current protocols against the attack implied by the results here, the working parameters have to be increased so much that the system will become impractical.

However, in order to use our approach against newly proposed protocols based on the braid group (see [4]), or against similar protocols based on other finitely generated groups, one must first find a good length function for the specific problem.

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