

A MODIFICATION OF SHANKS' BABY-STEP GIANT-STEP ALGORITHM

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ABSTRACT. I describe a modification to Shanks' baby-step giant-step algorithm for computing the order n of an element g of a group G , assuming n is finite. My method has the advantage of being able to compute n quickly, which Shanks' method fails to do when the order of G is infinite, unknown, or much larger than n . I describe the algorithm in detail. I also present the results of implementations of my algorithm, as well as those of a similar algorithm developed by Buchmann, Jacobson, and Teske, for calculating the order of various ideal classes of imaginary quadratic orders.

1. INTRODUCTION

Shanks' baby-step giant-step algorithm [1, 2] is a well-known procedure for finding the order n of an element g of a finite group G . Running it involves $2\sqrt{K} + O(1)$ group multiplications (GM), and $\sqrt{K} + O(1)$ table lookups (TL), where K is an upper bound on n (for instance, one often uses $K = |G|$). Often, however, K is unknown or much larger than n . In this case, a faster algorithm is desired. Here is my main result, to be proven later:

Theorem 1.1. *Let G be a group for which it is possible to compute the product of any two elements, to determine whether two elements are equal, and to determine whether a given element is equal to 1, the identity of G , and let g be an element of G of finite order $n > 2$. Then there exists a deterministic algorithm which determines the order n of g , using $GM = 2\lceil\sqrt{2(n-1)}\rceil - 2$ group multiplications and $TL = \lceil\sqrt{2(n-1)}\rceil - 1$ table lookups. (Here, $\lceil x \rceil$ denotes the nearest integer to x .)*

2. THE ORDER ALGORITHM

My algorithm is similar to Shanks' in that one still compares powers g^{t_j} of g (giant steps) to an updated hash table of pre-computed consecutive powers g^i for $1 \leq i \leq v$ (baby steps). However, with my algorithm, one does not need an upper bound on n . Instead, the giant steps are not constant, but grow linearly. Specifically, the sequence $(t_j)_{j=0}^\infty$ is defined recursively as follows:

$$(1) \quad \begin{aligned} t_0 &= 2v; \\ t_{j+1} &= t_j + j + v + 1 \quad (j \geq 0). \end{aligned}$$

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- (17) $n = t - i$ /* order of g */
- (18) **return** (n)
- (19) **break while**
- (20) **else**
- (21) $a = g * a; j = j + 1; R = R \cup \{(a, j + v)\}$
/*baby step */
- (22) $b = a * b; t = t + j + v$ /* giant step */
- (23) **fi**
- (24) **od**
- (25) **fi**
- (26) **fi**

Theorem 2.2. *For the above algorithm, we have*

$$GM = 2 \lceil \sqrt{2n + v(v - 3)} \rceil - v$$

and

$$TL = \lceil \sqrt{2n + v(v - 3)} \rceil - v + 1$$

if $n > v$. If $n \leq v$, we have $GM = n - 1$ and $TL = 0$. The algorithm also requires storing a total of

$$|R| = \lceil \sqrt{2n + v(v - 3)} \rceil + 1$$

group elements in the hash table in the case $n > v$.

Proof. In the case where $1 < n \leq v$, the order n of g will be found after computing the first n baby steps, which requires $n - 1$ group multiplications, no table lookups, and no storage. (If $n = 1$, no work is required, other than noting that $g = 1$.) If $n > v$, the order n of g will be found after $j + v + 1$ entries of the table are computed, as well as g^{t_j} , where j is the least integer such that $n \leq t_j$. We have

$$t_{j-1} = (j + 1)v + \frac{1}{2}j(j - 1) < n \leq t_j = (j + 2)v + \frac{1}{2}j(j + 1).$$

Using straightforward algebra, we find that

$$j = \lceil \sqrt{2(n - 1) + (v - \frac{3}{2})^2 - \frac{1}{2}} \rceil - v = \lceil \sqrt{2n + v(v - 3)} \rceil - v.$$

To compute the last $j + v - 1$ entries of the table as well as g^{t_i} for $0 \leq i \leq j$, a total of

$$GM = 2j + v = 2 \lceil \sqrt{2n + v(v - 3)} \rceil - v$$

group multiplications and

$$TL = j + 1 = \lceil \sqrt{2n + v(v - 3)} \rceil - v + 1$$

table lookups are required. (The first two elements of the table are not computed, just initialized.) It is also necessary to store the $|R| = j + v + 1 = \lceil \sqrt{2n + v(v - 3)} \rceil + 1$ group elements g^i ($0 \leq i \leq j + v$) in the table. QED

Setting $v = 2$, we find that

$$\text{GM} = 2\lceil\sqrt{2(n-1)}\rceil - 2$$

and

$$\text{TL} = \lceil\sqrt{2(n-1)}\rceil - 1,$$

if $n > 2$, proving Theorem 1.1.

QED

The speed of my algorithm can be improved slightly, since g^i need not be computed twice if i belongs to the sequence (t_j) of giant steps. This will reduce GM by $O(\sqrt{j}) = O((n+v^2)^{\frac{1}{4}})$, without affecting TL. However, it also requires that one store an additional j group elements, so that as n gets large, the storage requirements are nearly doubled, whereas the computing time is only reduced by a fraction which tends to zero. Thus, this improvement is impractical for large n .

3. COMPARISON WITH ALGORITHM OF BUCHMANN, JACOBSON, AND TESKE [1]

Here I present results of the implementation of my algorithm to the calculation of the orders of four ideal classes of each of three imaginary quadratic number fields with discriminants $\Delta = -4(10^8 + 1)$, $-4(10^{10} + 1)$, and $-4(10^{12} + 1)$. I wrote the program myself in Java, using Metrowerks CodeWarrior. I also wrote a version which implements the algorithm of Buchmann, Jacobson, and Teske [1], which I will refer to henceforth as the BJT algorithm. Both programs appear as Java applets on my webpage; the interested reader can run both algorithms and look at the source code [3]. For each of the twelve ideal classes I considered, I ran each algorithm with five different values of v , the initial giant step size, namely $v = 2$, $|\Delta|^{\frac{1}{4}}/8$, $|\Delta|^{\frac{1}{4}}/4$, $|\Delta|^{\frac{1}{4}}/2$, and $|\Delta|^{\frac{1}{4}}$.

In each of the following tables, I_p denotes the prime ideal lying above the rational prime p of the imaginary quadratic number field K with discriminant Δ , and (I_p) is the ideal class of the class group $G = \text{Cl}(K)$ containing I_p . The numbers in bold indicate which algorithm involves the lesser of the quantity shown. In the case of a tie, each value is printed in italics. The numbers in brackets indicate which of the

TABLE 1. Order algorithm, $v = 2$

Δ	p	$ (I_p) $	My algorithm			BJT		
			GM	TL	$ R $	GM	TL	$ R $
$-4(10^8 + 1)$	5	228	40	20	[22]	41	21	[16]
	3	456	58	<i>29</i>	[31]	66	<i>29</i>	[32]
	7	1368	102	51	[53]	122	52	[64]
	11	4104	180	90	[92]	230	95	[128]
$-4(10^{10} + 1)$	5	4033	178	89	[91]	164	94	[64]
	3	16132	358	179	[181]	324	189	[128]
	13	24198	438	219	[221]	485	221	256
	7	48396	620	310	[312]	580	316	256
$-4(10^{12} + 1)$	11	13040	320	160	[162]	299	164	[128]
	59	23472	432	216	[218]	482	218	256
	5	29340	482	<i>241</i>	[243]	505	<i>241</i>	256
	3	117360	966	483	[485]	1005	484	512

TABLE 2. Order algorithm, $v = |\Delta|^{\frac{1}{4}}/8$

Δ	p	$ \langle(I_p)\rangle $	My algorithm			BJT		
			GM	TL	$ R $	GM	TL	$ R $
$-4(10^8 + 1)$	5	228	[36]	10	28	[35]	12	18
	3	456	[50]	17	35	63	21	36
	7	1368	92	38	56	124	45	72
	11	4104	166	75	93	162	83	72
$-4(10^{10} + 1)$	5	4033	[154]	50	106	184	64	112
	3	16132	320	133	189	389	156	224
	13	24198	398	172	228	425	192	[224]
	7	48396	576	261	317	533	300	[224]
$-4(10^{12} + 1)$	11	13040	[299]	62	239	[259]	74	176
	59	23472	[381]	103	280	[318]	133	[176]
	5	29340	[421]	123	300	[351]	166	[176]
	3	117360	853	339	516	783	421	[352]

TABLE 3. Order algorithm, $v = |\Delta|^{\frac{1}{4}}/4$

Δ	p	$ \langle(I_p)\rangle $	My algorithm			BJT		
			GM	TL	$ R $	GM	TL	$ R $
$-4(10^8 + 1)$	5	228	45	<i>6</i>	41	48	<i>6</i>	36
	3	456	55	11	46	[54]	12	36
	7	1368	[89]	28	63	115	36	72
	11	4104	159	63	98	153	74	72
$-4(10^{10} + 1)$	5	4033	172	31	143	[156]	36	112
	3	16132	[310]	100	212	361	128	224
	13	24198	[380]	135	247	397	164	[224]
	7	48396	548	219	331	505	272	[224]
$-4(10^{12} + 1)$	11	13040	422	35	389	401	36	354
	59	23472	474	61	415	431	66	354
	5	29340	502	75	429	447	82	354
	3	117360	[844]	246	600	[696]	331	354

five giant-step sizes used was optimal for the given ideal class and algorithm. Note that in the case of $\Delta = -4(10^{10} + 1)$, and $v = 2$, $|\Delta|^{\frac{1}{4}}/2$, and $|\Delta|^{\frac{1}{4}}$ (middle four rows of Tables 1, 4, and 5) my results for the BJT algorithm agree with those in [1].

As can be seen from the above tables, the speed and storage of my algorithm are very close to that of Buchmann et al. In most cases, GM and TL are within 10% of each other. My method seems to have the advantage of requiring fewer table lookups; in each case, TL for my algorithm is no greater than for BJT. GM appears to be comparable for the two algorithms, although mine seems to involve fewer group multiplications for small v than theirs. For larger v , their algorithm appears to work better. In the case of calculating orders of ideals of imaginary quadratic fields, my algorithm appears to be optimal for v near $|\Delta|^{\frac{1}{4}}/4$, whereas the BJT algorithm

TABLE 4. Order algorithm, $v = |\Delta|^{\frac{1}{4}}/2$

Δ	p	$ \langle(I_p)\rangle $	My algorithm			BJT		
			GM	TL	$ R $	GM	TL	$ R $
$-4(10^8 + 1)$	5	228	75	3	74	81	3	70
	3	456	81	6	77	84	6	70
	7	1368	103	17	88	[97]	19	70
	11	4104	[157]	44	115	[136]	58	[70]
$-4(10^{10} + 1)$	5	4033	256	17	241	251	18	224
	3	16132	348	63	287	[305]	72	224
	13	24198	402	90	314	[341]	108	[224]
	7	48396	[540]	159	383	[449]	216	[224]
$-4(10^{12} + 1)$	11	13040	741	18	725	738	18	708
	59	23472	769	32	739	753	33	708
	5	29340	785	40	747	761	41	708
	3	117360	1005	150	857	885	165	708

TABLE 5. Order algorithm, $v = |\Delta|^{\frac{1}{4}}$

Δ	p	$ \langle(I_p)\rangle $	My algorithm			BJT		
			GM	TL	$ R $	GM	TL	$ R $
$-4(10^8 + 1)$	5	228	141	[1]	142	153	[1]	142
	3	456	145	[3]	144	155	[3]	142
	7	1368	157	[9]	150	161	[9]	142
	11	4104	191	[26]	167	180	[28]	142
$-4(10^{10} + 1)$	5	4033	461	[8]	455	467	[9]	448
	3	16132	513	[34]	481	494	[36]	448
	13	24198	547	[51]	498	512	[54]	448
	7	48396	639	[97]	544	566	[108]	448
$-4(10^{12} + 1)$	11	13040	1430	[9]	1423	1437	[9]	1414
	59	23472	1444	[16]	1430	1444	[16]	1414
	5	29340	1452	[20]	1434	1448	[20]	1414
	3	117360	1572	[80]	1494	1510	[82]	1414

appears to work better for v near $|\Delta|^{\frac{1}{4}}/2$. Upon differentiating the equation for GM in Theorem 2.2 with respect to v (neglecting the integer rounding), we find that the optimal value of v should be asymptotic to $\sqrt{\frac{2}{3}n}$ for my algorithm. When one has no good lower bound on n , one should use $v = 2$, in which case my algorithm appears to be faster than the BJT algorithm.

4. A BOUND FOR SIMILAR METHODS

It would be of interest to find a lower bound on GM for all similar methods. For the purpose of this calculation, we will neglect table lookups; thus we will assume that every power of g calculated is tabulated as soon as it is compared with all previous table entries, assuming no match is found. Although this may make TL

unnecessarily high, it will ensure that GM is as small as possible. Let $(a_i)_{i=0}^{\infty}$ be the chronological sequence of powers of g calculated in determining n , where $a_0 = 0$ and $a_1 = 1$. (The sequence (a_i) must be infinite to allow for the determination of arbitrarily large n .) Since every power of g is obtained by multiplying two previously calculated powers of g , the sequence (a_i) must be an addition sequence, i.e. for every integer $k \geq 2$, we must have $a_k = a_i + a_j$ for some positive integers $i, j < k$, possibly with $i = j$. Also, every positive integer n must be expressible as the difference between two elements of the sequence, i.e. we must have $n = a_{i_2} - a_{i_1}$ for some i_1 and i_2 . Aside from these two restrictions, we make no further restrictions on the sequence (a_i) . Let $i(n) = \min\{\max(i_1, i_2) : n = a_{i_2} - a_{i_1}\}$. Then if the order of g is n , we require $i(n) - 1$ group multiplications to determine n .

Theorem 4.1. *There exist infinitely many positive integers m such that $i(m) \geq \sqrt{2m}$.*

Proof. Given a fixed positive integer n , let m be a positive integer not exceeding n such that $i(m)$ is maximal, i.e. we have $i(m) = \max\{i(k) : 1 \leq k \leq n\}$. Then every positive integer not exceeding n is the difference of two numbers in the sequence whose indices do not exceed $i(m)$. This implies

$$m \leq n \leq \binom{i(m)}{2} = \frac{i(m)(i(m) - 1)}{2} \leq \frac{i(m)^2}{2},$$

the binomial coefficient being an upper bound on the number of distinct differences among the first $i(m)$ terms of the sequence. Since the right side grows at least as fast as n , infinitely many values of m are needed as n grows. Solving the above inequality for $i(m)$, we find that $i(m) \geq \sqrt{2m}$ for each of these m . QED

Theorem 4.1 may be restated as follows: The number of group multiplications required to calculate *arbitrary* n is bounded below by $C\sqrt{n}$, where

$$C := \limsup_{m \rightarrow \infty} \frac{i(m)}{\sqrt{m}} \geq \sqrt{2}.$$

In the case $v = 2$, my method yields a constant $C = 2\sqrt{2}$, twice the theoretical lower bound. Thus, any similar method would involve no less than half as many group multiplications as mine.

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