

# Some Factorizations of $2^n \pm 1$ and Related Results

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**1. Introduction.** In this paper we present a collection of complete factorizations obtained over the past year and a half on the IBM 7090-94 at the UCLA Computing Facility and the Computer Center at the University of California, Berkeley.

The numbers given here are generally of the three forms:  $2^n \pm 1$ ,  $2^{2^n} \pm 2^n + 1$ , and  $2^{2^{n+1}} \pm 2^{n+1} + 1$ , the latter trinomials occurring naturally in  $2^{3^n} \mp 1 = (2^n \mp 1)(2^{2^n} \pm 2^n + 1)$  and the Aurifeuillian factorization  $2^{4^{n+2}} + 1 = (2^{2^{n+1}} - 2^{n+1} + 1)(2^{2^{n+1}} + 2^{n+1} + 1)$ . As is customary, we have not removed those algebraic factors of  $2^n - 1$  which would produce a quotient more complicated than a trinomial. (As usual, a prime factor of  $2^n - 1$  is called "algebraic" if it divides  $2^k - 1$  for some  $k < n$ . Otherwise it is called "primitive".) To distinguish the remaining algebraic factors from the primitive factors, we have given the latter in boldface.

The numbers we have investigated were chosen with an eye to their size, since in general nothing but frustration can be expected to come from an attack on a number of 25 or more digits, even with the speeds available in modern computers. In view of this, factorization (15) is somewhat remarkable.

In the eight factorizations (2), (6), (7), (15), (25), (36), (37), and (39), the new factors were discovered by expressing the composite cofactors as a difference of squares (by "cofactor" we mean the quotient that remains when the known factors are removed). By this means the cofactors were split into pieces that could be identified as primes by either searching for factors up to their square roots, or by testing them for primality. (This method was also used to produce the auxiliary factorizations in (29) and (33).) A brief discussion of the difference of squares method will be given in Section 2.

In the remaining factorizations the completeness was shown by testing their cofactors for primality. The primality tests which were used will be discussed in Section 3.

The paper concludes with a collection of results, which include among others the current status of the numbers  $(10^p - 1)/9$ ,  $p$  prime, of the "original" Mersenne numbers, and of the complete factorizations of  $2^n \pm 1$ .

**2. Factorization by a Difference of Squares.** (a) The problem of finding factors of a number  $N = 2k + 1$  is solved if we can express  $N$  as  $x^2 - y^2$  in a nontrivial way (by trivial we mean  $2k + 1 = (k + 1)^2 - k^2$ ). The seven factorizations in (2), (6), (7), (15), (29), (37), and (39) were obtained in this way by means of a computer program written by the first author.

This program is based on the familiar exclusion method of Gauss (see Uspensky

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and Heaslet [20], Kraitchik [6]) in which the Diophantine equation

$$(A) \quad N = x^2 - y^2$$

is effectively replaced by the combinatorial problem of solving the set of simultaneous congruences  $y^2 \equiv x^2 - N \pmod{E}$  with various "exclusion" moduli  $E$ . The requirement that  $x^2 - N$  be a quadratic residue for each  $E$  places a strong restriction on the values of  $x$ . In fact, since each congruence is solvable for only about half of the  $E$  values of  $x$  for each  $E$ , only one  $x$  value in  $2^s$  will generally survive the exclusion when  $s$  moduli are used.

By experiment it has been found for the IBM 7090 that 21 or 22 moduli are sufficient to sieve out all but a small number of  $x$  values, each of which must then be tried in (A). The speed of the sieving program is approximately 150,000 values per second, which is achieved by using 10 or 11 double moduli (such as  $E = 17 \cdot 83$ ) and by operating only at the word level. The method itself is most successful when  $N$  can be split into two factors that are close together, as in the auxiliary factorization in (29), where the factors 1061802263 and 1071160627 were discovered in less than a second!

The three factorizations in (25), (33), and (36) were obtained on the new delay-line sieve of D. H. Lehmer at the University of California, Berkeley. This electronic sieve, which became operative on December 1, 1965, is the most recent in a series of remarkable sieving machines that have been built by Professor Lehmer and his associates over the last 40 years (see Lehmer [7], [8], [9], and D. N. Lehmer [16]). The speed of the sieve is  $10^6$  values per second, a factor of 7 over the speed of the sieving program on the 7090.

(b) When  $N$  has a special form, it is often possible to develop modular restrictions on  $x$  or  $y$  which limit them to a *single* residue class. These restrictions, when they are introduced as a change of variable, considerably reduce the magnitude of the problem when the sieving is carried out on the new variable. For instance, if  $N \equiv 2 \pmod{3}$ , then the congruence  $2 \equiv x^2 - y^2 \pmod{3}$  implies that  $3 \mid x$ ; for if  $x \equiv \pm 1 \pmod{3}$ , then  $y^2 \equiv 2 \pmod{3}$ , which is impossible. Similarly, if  $N \equiv 1 \pmod{3}$ , then  $3 \mid y$ .

In the present case where  $N$  is a primitive factor of  $2^n - 1$  (that is,  $N$  is a product of primitive prime factors), we can show that  $x$  belongs to a certain arithmetic sequence with a rather large difference. This follows from the known fact that all the factors of  $N$  are  $\equiv 1 \pmod{n}$ . If  $N = (x - y)(x + y)$ , we can put  $x - y = tn + 1$  and  $x + y = un + 1$ , which imply

$$(B) \quad N = tun^2 + n(t + u) + 1 \quad \text{and} \quad 2x = n(t + u) + 2.$$

Hence,

$$(C) \quad N = tun^2 + 2x - 1, \quad \text{or} \quad x \equiv \frac{1}{2}(N + 1) \pmod{n^2} \quad \text{for } n \text{ odd,}$$

and

$$(D) \quad x \equiv \frac{1}{2}(N + 1) \pmod{n^2/2} \quad \text{for } n \text{ even (see Lehmer [10]).}$$

Also, (C) can be improved by noting that if  $N \mid 2^n - 1$ ,  $n$  odd, then  $[2^{(n+1)/2}]^2 \equiv 2 \pmod{N}$ . But if 2 is a quadratic residue of  $N$ , then every factor of  $N$  will be congruent to  $\pm 1 \pmod{8}$ . If further,  $N \equiv -1 \pmod{8}$ , then there is at least one

factorization  $N = ab$ , where  $a = tn + 1 \equiv 1 \pmod{8}$  and  $b = un + 1 \equiv -1 \pmod{8}$ . Thus,  $8 \mid t$  and  $2 \mid u$ , and (C) becomes  $x \equiv \frac{1}{2}(N + 1) \pmod{8n^2}$ . If, on the other hand,  $N \equiv 1 \pmod{8}$ , the best that can be obtained is that  $2 \mid t$  and  $2 \mid u$ , whence  $x \equiv \frac{1}{2}(N + 1) \pmod{2n^2}$ .

We observe in (D) that the modulus can be increased by a factor of 2 if  $(N - 1)/n$  is odd. (This condition often holds, as in the factorizations (2), (7), (15), and (39).) If we rewrite (B) as  $(N - 1)/n = tun + t + u$ , then since  $n$  is even,  $t + u$  is odd. Hence,  $tu$  is even, say  $2m$ , and (C) becomes  $N = 2mn^2 + 2x - 1$ . Thus,  $x \equiv \frac{1}{2}(N + 1) \pmod{n^2}$ .

**3. Primality Testing.** (a) The main theorem we have used for primality testing is due to Lehmer [11]:

**THEOREM 1.** *If there exists an  $a$  such that  $a^{N-1} \equiv 1 \pmod{N}$ , but  $a^{(N-1)/q} \not\equiv 1 \pmod{N}$  for every prime divisor  $q$  of  $N - 1$ , then  $N$  is prime.*

Since this theorem requires a knowledge of the complete factorization of  $N - 1$ , as well as a successful choice of the base  $a$  for which all the hypotheses hold, a certain amount of auxiliary calculation is necessary before the primality test can be completed (see Robinson [17]).

Accompanying the factorizations below, in which Theorem 1 was used, are the complete factorization of  $N - 1$  and a primitive root  $a$  of  $N$ , to assist anyone who wishes to repeat our testing.

It is clear in some cases that the factorization of  $N - 1$  is materially assisted by the form of  $N$  (see Lehmer [11]) as in (12), where  $N = (2^{104} + 1)/257$  and  $N - 1 = 2^8(2^{96} - 1)/257$ , which readily factors.

In many of the calculations, such as (17), the theorem had to be applied several times to the cofactors at various "levels" before a final decision could be made concerning the primality of the original cofactor (see Brillhart [1]). In such cases the base used at each level is given in addition to the relevant factorization of one less than the cofactor under consideration.

It will be noted that the size of the bases used in testing (31) implies it was difficult to find a small primitive root for which the hypotheses of the theorem were all satisfied. It is of interest, then, to observe that the condition that the hypotheses hold for the *same* base can be relaxed to allow a change of base, if needed, for each prime factor of  $N - 1$ . In fact, we now have the following theorem of the second author:

**THEOREM 2.** *Let  $N$  be an odd integer  $> 1$ . If  $N - 1 = \prod_{p_i}^{\alpha_i} q_i$ ,  $q_i$  prime, and if for each  $q_i$  there exists an  $a_i$  for which  $a_i^{N-1} \equiv 1 \pmod{N}$ , but  $a_i^{(N-1)/q_i} \not\equiv 1 \pmod{N}$ , then  $N$  is prime.*

*Proof.* Let  $a_i$  belong to the exponent  $d_i \pmod{N}$ . Then  $d_i \mid \phi(N)$ . Let  $D = LCM(d_i)$ . Then  $D \mid \phi(N)$ . But  $d_i \mid N - 1$ , and  $d_i \nmid (N - 1)/q_i$ . Hence,  $q_i^{\alpha_i} \mid d_i$  and thus  $q_i^{\alpha_i} \mid D$ . Then  $N - 1 \mid D$ , and finally  $N - 1 \mid \phi(N)$ , which implies that  $N$  is prime.

It is clear in practice that Theorem 2 is an improvement on Theorem 1, since if an  $a$  can be found for which  $a^{N-1} \equiv 1 \pmod{N}$ , but  $a^{(N-1)/q} \not\equiv 1 \pmod{N}$  for a particular  $q$ , then that  $q$  has been settled once and for all, regardless of what bases are used for the other  $q$ 's.

To illustrate Theorem 2 we note that the primality of the cofactor in (12)

can be decided with  $a = 3$  for  $q = 3, 5, 13, 17, 97, 193, 241, 673, 65537,$  and  $22253377$ ; with  $a = 7$  for  $q = 7$ ; and with  $a = 11$  for  $q = 2$ . However, in the list below we have taken the trouble to find a primitive root, rather than apply Theorem 2.

It should be pointed out that there is another theorem of Lehmer (p. 331 of [11]), which is generally superior to Theorem 2 in that it allows a change of base and requires that  $N - 1$  be factored only up to the point where its factored part exceeds its unfactored part. Since no advantage was gained from this theorem in the present investigation, where either the full factorization of  $N - 1$  was known, or not enough was known to apply this theorem, we have not used it here (see Theorem 3, p. 704 in Robinson [17]).

(b) Recently another test for primality has been programmed for the IBM 7090 by D. H. Lehmer. This test is based on a theorem concerning the divisibility properties of the Lucas sequences  $U_{n+1} = PU_n - QU_{n-1}$ ,  $n \geq 1$ ,  $U_0 = 0$ ,  $U_1 = 1$ ,  $P$  and  $Q$  integers (see Lehmer [12, p. 442]): If  $U_{N+1} \equiv 0 \pmod{N}$  and if  $U_{m_i} \not\equiv 0 \pmod{N}$ , where  $m_i = (N + 1)/q_i$  for each prime factor  $q_i$  in  $N + 1$ , then  $N$  is a prime.

In the testing program,  $P$  is taken to be 1 and  $Q$  is chosen so that  $(D/N) = -1$  and  $(QD, N) = 1$ , where  $D = 1 - 4Q$ . A discussion of this test will appear elsewhere in a paper of Professor Lehmer (for a special case see p. 18 of Lehmer [13]). We have used this program to show the completeness of (32) and the factorization of  $2^{109} - 1$  in Section 4.

The advantage of this test, of course, is that it employs the factorization of  $N + 1$ , rather than  $N - 1$ , so that in case the complete factorization of  $N - 1$  is not obtainable (or even the factorization to the square root of  $N - 1$ ), we may still be able to factor  $N + 1$ . In those cases mentioned above where the factorization of  $N + 1$  was used, we have given the value of  $Q$  at each level.

**4. Miscellaneous Results.** We begin this collection of results by pointing out that the factorizations (1)–(4), (7), (11), (14), (15), (17), (20), and (29) supplement the earlier paper of Brillhart [2] and complete the table there through  $p < 100$ . In this listing we have made no attempt to credit the previously known factors to their original discoverers; however, we would like to mention that the 7-digit factors in (34) and (39) are due to R. M. Merson, and were transmitted to us by K. R. Isemonger. Many of the factors, of course, can be found in Cunningham [3].

We have verified the following two complete factorizations due respectively to D. H. Lehmer (1957, unpublished):

$$2^{93} - 2^{47} + 1 = 5 \cdot 8681 \cdot 49477 \cdot 4611545283086450689,$$

$$N - 1 = 2^{16} \cdot 3 \cdot 7 \cdot 31 \cdot 151 \cdot 715827883, \quad a = 11;$$

and E. Gabard [4]:

$$2^{109} - 1 = 745988807 \cdot 870035986098720987332873,$$

$$N + 1 = 2 \cdot 3 \cdot 67 \cdot 83 \cdot 233 \cdot 111912126900880183, \quad Q = 5,$$

$$N_1 - 1 = 2 \cdot 3 \cdot 503 \cdot 1801 \cdot 7643 \cdot 2693893, \quad a = 3.$$

TABLE 1

| $p$  | Character of $2^p - 1$   |
|--|--|
| 2, 3, 5, 7, 13, 17, 19, 31, 61, 89, 107, 127<br>(All other $p$ under 135), 151, 163, 179, 181<br>167, 197, 233, 239, 241<br>157, 173, 191, 193, 211, 223, 229, 251<br>137, 139, 149, 199, 227, 257 | Prime<br>Composite. Completely factored<br>Cofactor is a pseudoprime<br>Cofactor is composite<br>Composite but no factor known |

In Brillhart [1] the numbers  $N_p = (10^p - 1)/9$ ,  $p$  prime, are shown to be prime for  $p = 2, 19$ , and  $23$ , and for no other  $p \leq 109$ . We have extended the search for primes of this form, but there are no further primes for  $p < 359$ . This result was obtained by showing that  $a^{N_p-1} \not\equiv 1 \pmod{N_p}$  for those  $N_p$  for which no factor was known. For each  $N_p$  this test was run twice for  $a = 3$  with complete agreement in the final remainders.

We have also examined the classical Mersenne numbers  $M_p = 2^p - 1$ ,  $p$  prime  $\leq 257$ , whose cofactors were of unknown character. The results of this investigation are given in Table 1 below. This table should be self-explanatory, except perhaps for the term "pseudoprime", which is used in the literature in several different ways.

In our usage, the term refers to an integer  $N > 2$  which satisfies the congruence  $a^{N-1} \equiv 1 \pmod{N}$  for some base  $a$ ,  $1 < a < N - 1$ . This definition is in contrast to several others in which a "pseudoprime" is taken to be some composite solution of this congruence (see Shanks [19]).

We have found in practice that a number  $N$  with no particular form will generally turn out to be a prime if it is a pseudoprime for even a single base. This is due, no doubt, to the relative scarcity of composite pseudoprimes. A further indication of this scarcity is found in the fact that we have never encountered a composite pseudoprime in testing hundreds of numbers, even though infinitely many of them are known to exist (see Lehmer [14], Robinson [17]).

On the other hand, there are infinitely many numbers  $N$  with a special form, which we know are pseudoprimes for a particular base, but which we still cannot conclude are likely to be prime for this reason. A pertinent example of this is:  $a = 2$  and  $N$  a primitive factor of  $2^n - 1$ , in which case we know that  $N = kn + 1$ , and hence that  $2^{N-1} = 2^{kn} \equiv 1 \pmod{N}$ . Thus, the term "pseudoprime" as used in Table 1 should be understood to refer to the base 3.

We conclude these results with a list of all the cases of complete factorizations of  $2^n \pm 1$  that we have seen (Table 2). This brings up to date similar lists in Lehmer [15] and Robinson [18]. The more recent factorizations will be found in Math. Comp. (MTAC) with the exception of the following (listed with the name of their discoverer):

$$2^{78} - 2^{39} + 1 = 3 \cdot 19 \cdot 5302306226370307681801 \quad (\text{Gabard})$$

$$2^{81} - 2^{41} + 1 = 13 \cdot 37 \cdot 279073 \cdot 3618757 \cdot 4977454861 \quad (\text{Merson})$$

$$2^{86} + 2^{43} + 1 = 7 \cdot 11053036065049294753459639 \quad (\text{Gabard})$$

$$\begin{aligned}
2^{101} - 1 &= 7432339208719 \cdot 341117531003194129 && \text{(G. D. Johnson)} \\
2^{101} + 1 &= 3 \cdot 845100400152152934331135470251 && \text{(Gabard)} \\
2^{115} - 2^{58} + 1 &= 5^2 \cdot 461 \cdot 1013 \cdot 1657 \cdot 5981 \cdot 359006912765190408181 && \\
&&& \text{(Isemonger)} \\
2^{115} + 1 &= 3 \cdot 11 \cdot 691 \cdot 2796203 \cdot 1884103651 \cdot 345767385170491 && \\
&&& \text{(Isemonger)} \\
2^{119} - 2^{60} + 1 &= 113 \cdot 137 \cdot 953 \cdot 2381 \cdot 42841 \cdot 823481 \cdot 536296539263941 && \\
&&& \text{(Isemonger)} \\
2^{122} + 2^{61} + 1 &= 7 \cdot 367 \cdot 55633 \cdot 37201708625305146303973352041 && \\
&&& \text{(Gabard)} \\
2^{125} + 2^{63} + 1 &= 41 \cdot 101 \cdot 7001 \cdot 8101 \cdot 3775501 \cdot 47970133603445383501 && \\
&&& \text{(Isemonger)} \\
2^{143} + 2^{72} + 1 &= 5 \cdot 397 \cdot 1613 \cdot 25741 \cdot 3426853 \cdot 9467173 && \\
&\quad \cdot 4170165570896115649 && \text{(Isemonger)} \\
2^{147} - 2^{74} + 1 &= 5 \cdot 29 \cdot 197 \cdot 14449 \cdot 540961 \cdot 19707683773 && \\
&\quad \cdot 40544859693521152369 && \text{(Isemonger)} \\
2^{153} - 2^{77} + 1 &= 13 \cdot 37 \cdot 137 \cdot 953 \cdot 2582029 \cdot 4260133 \cdot 1326700741 && \\
&\quad \cdot 12458723489217613 && \text{(Merson)}
\end{aligned}$$

TABLE 2

$2^n - 1$ ,  $n$  odd:  $n = 1-123, 127-135, 147, 151-155, 159, 163, 165, 171, 175, 179, 181, 189, 195, 201, 225, 255, 315, 521, 607, 1279, 2203, 2281, 3217, 4253, 4423, 9689, 9941, 11213$ .

$2^n + 1$ :  $n = 0-102, 104-118, 120, 122, 123, 126, 129, 130, 132, 134, 135, 138, 141, 142, 144, 146-148, 150, 154, 158, 162, 165, 166, 170, 174, 178, 182, 186, 190, 194, 195, 198, 201, 206, 210, 214, 222, 226, 230, 234, 246, 250, 270$ .

$2^n - 2^m + 1$ ,  $n = 2m - 1$ :  $n = 1-99, 103-107, 111-119, 123-127, 135, 141, 147, 151, 153, 165, 167, 239, 241, 353, 367, 457$ .

$2^n + 2^m + 1$ ,  $n = 2m - 1$ :  $n = 1-99, 103-117, 123, 125, 129, 135, 143, 157, 163, 171, 283, 379$ .

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*Complete Factorizations*

$$\begin{aligned}
1. \quad 2^{79} + 2^{40} + 1 &= 5 \cdot 317 \cdot 381364611866507317969 \\
N - 1 &= 2^4 \cdot 3^2 \cdot 79 \cdot 36558773 \cdot 916978591, \quad a = 11,
\end{aligned}$$

2.  $2^{83} + 2^{42} + 1 = 997 \cdot 46202197673 \cdot 209957719973$
3.  $2^{89} - 2^{45} + 1 = 1069 \cdot 579017791994999956106149$   
 $N - 1 = 2^2 \cdot 3^7 \cdot 89 \cdot 109 \cdot 6199 \cdot 1100639243449, \quad a = 6,$
4.  $2^{89} + 2^{45} + 1 = 5 \cdot 123794003928545064364330189$   
 $N - 1 = 2^2 \cdot 3^2 \cdot 23 \cdot 89 \cdot 397 \cdot 683 \cdot 2113 \cdot 2932031007403, \quad a = 6,$
5.  $2^{95} - 2^{48} + 1 = 41 \cdot 761 \cdot 525313 \cdot 2416923620660807201$   
 $N - 1 = 2^5 \cdot 5^2 \cdot 19 \cdot 159008132938211, \quad a = 13,$   
 $N_1 - 1 = 2 \cdot 5 \cdot 23 \cdot 31 \cdot 6829 \cdot 3265673, \quad a_1 = 17,$
6.  $2^{96} - 2^{48} + 1 = 1153 \cdot 6337 \cdot 38941695937 \cdot 278452876033$
7.  $2^{97} - 2^{49} + 1 = 389 \cdot 4657 \cdot 4059325597 \cdot 17637260034881$
8.  $2^{98} - 2^{49} + 1 = 3 \cdot 5419 \cdot 748819 \cdot 26032885845392093851$   
 $N - 1 = 2 \cdot 3^2 \cdot 5^2 \cdot 7^2 \cdot 13 \cdot 617 \cdot 147192338057, \quad a = 7,$
9.  $2^{98} + 2^{49} + 1 = 7^3 \cdot 337 \cdot 2741672362528725535068727$   
 $N - 1 = 2 \cdot 3 \cdot 7^2 \cdot 61 \cdot 337 \cdot 70687 \cdot 6417545220131, \quad a = 3,$
10.  $2^{102} + 2^{51} + 1 = 73 \cdot 919 \cdot 75582488424179347083438319$   
 $N - 1 = 2 \cdot 3^2 \cdot 17 \cdot 67 \cdot 853 \cdot 5399 \cdot 800502326409847, \quad a = 6,$   
 $N_1 - 1 = 2 \cdot 3 \cdot 41 \cdot 43 \cdot 75676151107, \quad a_1 = 5,$
11.  $2^{103} + 2^{52} + 1 = 5 \cdot 17325013 \cdot 117070097457656623005977$   
 $N - 1 = 2^3 \cdot 59 \cdot 103 \cdot 162917 \cdot 14780882080883, \quad a = 19,$
12.  $2^{104} + 1 = 257 \cdot 78919881726271091143763623681$   
 $N - 1 = 2^8 \cdot 3^2 \cdot 5 \cdot 7 \cdot 13 \cdot 17 \cdot 97 \cdot 193 \cdot 241 \cdot 673 \cdot 65537 \cdot 22253377, \quad a = 61,$
13.  $2^{107} + 1 = 3 \cdot 643 \cdot 84115747449047881488635567801$   
 $N - 1 = 2^3 \cdot 5^2 \cdot 107 \cdot 3930642404161115957412877, \quad a = 41,$   
 $N_1 - 1 = 2^2 \cdot 3^2 \cdot 71 \cdot 747619 \cdot 1020797 \cdot 2015036747, \quad a_1 = 5,$
14.  $2^{107} - 2^{54} + 1 = 5 \cdot 857 \cdot 37866809061660057264219253397$   
 $N - 1 = 2^2 \cdot 19 \cdot 107 \cdot 353 \cdot 91813 \cdot 143675413657196977, \quad a = 21,$   
 $N_1 - 1 = 2^4 \cdot 3^2 \cdot 547 \cdot 1103 \cdot 1653701519, \quad a_1 = 5,$
15.  $2^{107} + 2^{54} + 1 = 843589 \cdot 8174912477117 \cdot 23528569104401$
16.  $2^{109} + 1 = 3 \cdot 104124649 \cdot 2077756847362348863128179$   
 $N - 1 = 2 \cdot 3 \cdot 29 \cdot 109 \cdot 21427369 \cdot 5112697847507, \quad a = 3,$
17.  $2^{109} + 2^{55} + 1 = 5669 \cdot 666184021 \cdot 171857646012809566969$   
 $N - 1 = 2^3 \cdot 3 \cdot 19 \cdot 109 \cdot 3457622042749267, \quad a = 7,$   
 $N_1 - 1 = 2 \cdot 3 \cdot 7 \cdot 82324334351173, \quad a_1 = 5,$   
 $N_2 - 1 = 2^2 \cdot 3 \cdot 210559 \cdot 32575469, \quad a_2 = 5,$
18.  $2^{110} + 2^{55} + 1 = 7 \cdot 151 \cdot 599479 \cdot 2048568835297380486760231$   
 $N - 1 = 2 \cdot 3 \cdot 5 \cdot 11 \cdot 31 \cdot 29527 \cdot 6781965931002463, \quad a = 6,$   
 $N_1 - 1 = 2 \cdot 3 \cdot 41 \cdot 491 \cdot 811 \cdot 69233797, \quad a_1 = 6,$
19.  $2^{111} - 2^{56} + 1 = 13 \cdot 593 \cdot 231769777 \cdot 1453030298001690873541$   
 $N - 1 = 2^2 \cdot 3 \cdot 5 \cdot 37 \cdot 109 \cdot 302663 \cdot 19839734921, \quad a = 7,$

20.  $2^{113} + 2^{57} + 1 = 5 \cdot 58309 \cdot 2362153 \cdot 15079116213901326178369$   
 $N - 1 = 2^6 \cdot 3^2 \cdot 7^2 \cdot 89 \cdot 113 \cdot 1373 \cdot 191281 \cdot 202277, \quad a = 11,$
21.  $2^{114} + 2^{57} + 1 = 73 \cdot 93507247 \cdot 3042645634792541312037847$   
 $N - 1 = 2 \cdot 3^2 \cdot 7 \cdot 19 \cdot 23^2 \cdot 7823 \cdot 307113018359177, \quad a = 6,$   
 $N_1 - 1 = 2^3 \cdot 156841 \cdot 244764617, \quad a_1 = 3,$
22.  $2^{116} + 1 = 17 \cdot 59393 \cdot 82280195167144119832390568177$   
 $N - 1 = 2^4 \cdot 13 \cdot 17 \cdot 29 \cdot 71 \cdot 89 \cdot 580231 \cdot 218844570055711, \quad a = 3,$   
 $N_1 - 1 = 2 \cdot 3 \cdot 5 \cdot 19 \cdot 23 \cdot 39371 \cdot 423991, \quad a_1 = 19,$
23.  $2^{117} - 2^{59} + 1 = 5 \cdot 109 \cdot 1613 \cdot 3121 \cdot 7489 \cdot 21841 \cdot 370244405487013669$   
 $N - 1 = 2^2 \cdot 3^4 \cdot 13 \cdot 1360283 \cdot 64620583, \quad a = 17,$
24.  $2^{121} - 1 = 23 \cdot 89 \cdot 727 \cdot 1786393878363164227858270210279$   
 $N - 1 = 2 \cdot 3^3 \cdot 11^2 \cdot 273399736511044418098908817, \quad a = 6,$   
 $N_1 - 1 = 2^4 \cdot 3^2 \cdot 47 \cdot 79 \cdot 103 \cdot 211 \cdot 75983 \cdot 309652459427, \quad a_1 = 10,$
25.  $2^{123} - 2^{62} + 1 = 5 \cdot 10169 \cdot 43249589 \cdot 802333429 \cdot 6027043735173469$   
 $N - 1 = 2^2 \cdot 3 \cdot 7 \cdot 41 \cdot 587 \cdot 27241 \cdot 109441, \quad a = 11,$
26.  $2^{123} + 2^{62} + 1 = 13 \cdot 2953 \cdot 181549 \cdot 12112549 \cdot 125965976976392564317$   
 $N - 1 = 2^2 \cdot 3 \cdot 41 \cdot 127 \cdot 467 \cdot 9803 \cdot 440360699, \quad a = 7,$
27.  $2^{125} - 2^{63} + 1 = 5^4 \cdot 28001 \cdot 96001 \cdot 268501 \cdot 94291866932171243501$   
 $N - 1 = 2^2 \cdot 5^3 \cdot 11 \cdot 557 \cdot 1603673 \cdot 19192897, \quad a = 29,$
28.  $2^{126} + 2^{63} + 1 = 262657 \cdot 1560007 \cdot 207617485544258392970753527$   
 $N - 1 = 2 \cdot 3^3 \cdot 7 \cdot 43 \cdot 109 \cdot 3449 \cdot 376889 \cdot 90150993481, \quad a = 5,$
29.  $2^{127} - 2^{64} + 1 = 509 \cdot 26417 \cdot 140385293 \cdot 90133566917913517709497$   
 $N - 1 = 2^3 \cdot 3 \cdot 127 \cdot 29571380222412571427, \quad a = 7,$   
 $N_1 - 1 = 2 \cdot 13 \cdot 1061802263 \cdot 1071160627, \quad a_1 = 6,$
30.  $2^{130} - 2^{65} + 1 = 3 \cdot 331 \cdot 107251 \cdot 22366891 \cdot 571403921126076957182161$   
 $N - 1 = 2^4 \cdot 3 \cdot 5 \cdot 13 \cdot 183142282412204152943, \quad a = 19,$   
 $N_1 - 1 = 2 \cdot 23 \cdot 3981353965482698977, \quad a_1 = 5,$   
 $N_2 - 1 = 2^5 \cdot 3 \cdot 71 \cdot 941 \cdot 52571 \cdot 11807701, \quad a_2 = 5,$
31.  $2^{130} + 2^{65} + 1 = 7 \cdot 79 \cdot 151 \cdot 121369 \cdot 134304196845099262572814573351$   
 $N - 1 = 2 \cdot 3^2 \cdot 5^2 \cdot 7 \cdot 11 \cdot 13 \cdot 298155615151735514647163, \quad a = 29,$   
 $N_1 - 1 = 2 \cdot 13 \cdot 19 \cdot 86573 \cdot 6971617904258551, \quad a_1 = 37,$   
 $N_2 - 1 = 2 \cdot 3 \cdot 5^2 \cdot 83 \cdot 559969309579, \quad a_2 = 37,$
32.  $2^{131} - 1 = 263 \cdot 10350794431055162386718619237468234569$   
 $N + 1 = 2 \cdot 3 \cdot 5 \cdot 7^2 \cdot 11^2 \cdot 2711 \cdot 21465522331181621122125609701, \quad Q = 17,$   
 $N_1 + 1 = 2 \cdot 3^3 \cdot 89^2 \cdot 30211 \cdot 1661126041959455923, \quad Q_1 = 29,$   
 $N_2 + 1 = 2^2 \cdot 389 \cdot 22901 \cdot 46616380229, \quad Q_2 = 1,$
33.  $2^{133} - 1 = 127 \cdot 524287 \cdot 163537220852725398851434325720959$   
 $N - 1 = 2 \cdot 3^4 \cdot 7 \cdot 19 \cdot 23 \cdot 73 \cdot 252313 \cdot 77555939 \cdot 231017337191, \quad a = 3,$



34.  $2^{134} - 2^{67} + 1 = 3 \cdot 2011 \cdot 9649 \cdot 6324667 \cdot 59151549118532676874448563$   
 $N - 1 = 2 \cdot 3^3 \cdot 7^2 \cdot 13 \cdot 67 \cdot 1381 \cdot 2861 \cdot 6496008606077, \quad a = 3,$
35.  $2^{134} + 2^{67} + 1 = 7 \cdot 1609 \cdot 22111 \cdot 87449423397425857942678833145441$   
 $N - 1 = 2^5 \cdot 3 \cdot 5 \cdot 13 \cdot 67 \cdot 1559 \cdot 4027 \cdot 15053 \cdot 1681973 \cdot 1315914679, \quad a = 29,$
36.  $2^{150} + 2^{75} + 1 = 73 \cdot 631 \cdot 23311 \cdot 115201 \cdot 617401 \cdot 1348206751$   
 $\cdot 13861369826299351$   
 $N - 1 = 2 \cdot 3^2 \cdot 5^2 \cdot 41 \cdot 1933 \cdot 388667231, \quad a = 3,$
37.  $2^{155} - 1 = 31^2 \cdot 311 \cdot 11471 \cdot 73471 \cdot 2147483647 \cdot 4649919401 \cdot 18158209813151$
38.  $2^{170} + 2^{85} + 1 = 7 \cdot 103 \cdot 151 \cdot 2143 \cdot 11119 \cdot 106591 \cdot 949111$   
 $\cdot 5702451577639775545838643151$   
 $N - 1 = 2 \cdot 3 \cdot 5^2 \cdot 11 \cdot 17 \cdot 1163 \cdot 1471 \cdot 5197 \cdot 43793 \cdot 522130351, \quad a = 13,$
39.  $2^{171} + 2^{86} + 1 = 13 \cdot 37 \cdot 25309 \cdot 131101 \cdot 160969 \cdot 525313 \cdot 5675149$   
 $\cdot 39291697 \cdot 99463730244517$
40.  $2^{175} - 1 = 31 \cdot 71 \cdot 127 \cdot 601 \cdot 1801 \cdot 39551 \cdot 122921 \cdot 60816001$   
 $\cdot 535347624791488552837151$   
 $N - 1 = 2 \cdot 5^2 \cdot 7 \cdot 97 \cdot 137 \cdot 331 \cdot 261389 \cdot 1330332599, \quad a = 13,$
41.  $2^{210} + 2^{105} + 1 = 73 \cdot 631 \cdot 23311 \cdot 92737 \cdot 649657 \cdot 870031 \cdot 983431$   
 $\cdot 29728307155963706810228435378401$   
 $N - 1 = 2^5 \cdot 3^2 \cdot 5^2 \cdot 7 \cdot 19 \cdot 3361 \cdot 11329 \cdot 3163739 \cdot 257706459649, \quad a = 23.$

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