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EXPLICIT PRIMALITY CRITERIA FOR $h \cdot 2^k \pm 1$

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Dedicated to the memory of D. H. Lehmer

ABSTRACT. Algorithms are described to obtain explicit primality criteria for integers of the form $h \cdot 2^k \pm 1$ (in particular with h divisible by 3) that generalize classical tests for $2^k \pm 1$ in a well-defined finite sense. Numerical evidence (including all cases with $h < 10^5$) seems to indicate that these finite generalizations exist for every h, unless $h = 4^m - 1$ for some m, in which case it is proved they cannot exist.

1. INTRODUCTION

In this paper we consider primality tests for integers n of the form $h \cdot 2^k \pm 1$. Since every integer is of that form, we first specify what we mean by this.

Throughout this paper, h will denote an odd positive integer. We shall consider the question of obtaining primality criteria for $n_k = h \cdot 2^k \pm 1$, for all k such that $2^k > h$.

Two classical results express that primality of $2^k \pm 1$ can be decided by a single modular exponentiation; indeed, for $2^k + 1$ one has

$$n = 2^k + 1 \text{ is prime} \iff 3^{(n-1)/2} \equiv -1 \mod n, \tag{1.1}$$

whereas for $2^k - 1$ the formulation is usually in terms of recurrent sequences, as given by Lucas [9] and Lehmer [7] (see also §2):

$$n = 2^k - 1 \text{ is prime} \iff e_{k-2} \equiv 0 \mod n, \tag{1.2}$$

where $e_0 = -4$, and $e_{j+1} = e_j^2 - 2$ for $j \geq 0$. Similar primality criteria exist for n of the form $h \cdot 2^k \pm 1$ with h not divisible by 3.

For fixed h divisible by 3, however, one has to allow a dependency on k in the starting values for the exponentiation (or the recursion, as in (1.2)) in the criterion for $h \cdot 2^k \pm 1$. The generalizations of the above primality criteria described in this paper will be explicit in the sense that for every k with $2^k > h$ an explicit starting value will be given, and finite in the sense that the set of starting values for fixed h will be finite.

It seems that with the exception of h of the form $4^m - 1$, such an explicit, finite generalization always exists. As part of the research for this paper, I

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constructed such solutions for every h up to 100000. For h of the form $4^m - 1$ it is proved that a finite set of starting values will never suffice.

2. Primality criteria

Explicit primality criteria for numbers of the form $h \cdot 2^k + 1$ are based on the following theorem. (For proofs of statements in this section, see [2, 10].)

(2.1) **Theorem.** *Let* $n = h \cdot 2^k + 1$ *with* $0 < h < 2^k$ *and* h *odd. If* $(\frac{D}{n}) = -1$, *then*

$$n \text{ is prime} \Longleftrightarrow D^{(n-1)/2} \equiv -1 \mod n. \tag{2.2}$$

Thus, finding D with Jacobi symbol $(\frac{D}{n}) = -1$ suffices to obtain an explicit primality criterion for $n = h \cdot 2^k + 1$. In practice, finding such D for given k is easily done by picking D at random, or by searching for the smallest suitable D. The latter strategy was for instance used by Robinson [12] in an early computer search for primes of the form $h \cdot 2^k + 1$ with $h < 100$ and $k < 512$; he found that he never needed D larger than 47.

However, one wonders whether it would be possible to prescribe D for fixed h. For that it suffices to solve the following problem.

(2.3) **Problem.** Given an odd integer $h > 1$. Determine a finite set $\mathscr{D}$ and for every positive integer $k \geq 2$ an integer $D \in \mathscr{D}$ such that $(\frac{D}{h \cdot 2^k+1}) \neq 1$ and $D \not\equiv 0 \mod h \cdot 2^k + 1$.

(2.4) *Remarks.* In what follows below, we will often write about a solution $\mathscr{D}$ to Problem (2.3), when we mean such a set together with a map $\mathbf{Z}_{\geq 2} \to \mathscr{D}$, which provides the explicit value for every k. This map will in our constructions be constant on the residue classes modulo some 'period' r.

Let some odd h be fixed. Suppose that $\mathscr{D}$ forms a solution to the problem described in (2.3), and let $D_k \in \mathscr{D}$ such that $(\frac{D_k}{h \cdot 2^k+1}) \neq 1$. If $(\frac{D_k}{h \cdot 2^k+1}) = -1$, then Theorem (2.1) provides an explicit primality test for $h \cdot 2^k + 1$, provided that $2^k > h$. If, on the other hand, $(\frac{D_k}{h \cdot 2^k+1}) = 0$ and $h \cdot 2^k + 1 \nmid D_k$, then both sides of (2.2) are false.

Since $(\frac{-D}{h \cdot 2^k+1}) = (\frac{D}{h \cdot 2^k+1})$ for $k > 1$, we will henceforth assume that $\mathscr{D}$ consists of positive integers.

(2.5) *Remark.* Notice that for some h it is even possible to solve Problem (2.3) with the stronger requirement that $(\frac{D_k}{h \cdot 2^k+1}) = 0$. This is for instance true for $h = 78557$: Selfridge noticed that $78557 \cdot 2^k + 1$ has a divisor in $\mathscr{D} = \{3, 5, 7, 13, 17, 241\}$ for every $k \geq 1$ [6, p. 42].

Next we describe primality criteria for numbers of the form $h \cdot 2^k - 1$. Whereas tests for $h \cdot 2^k + 1$ all took place within $\mathbf{Z}$ (or rather $\mathbf{Z}/n\mathbf{Z}$), we now pass to quadratic extensions. For a quadratic field $\mathbf{Q}(\sqrt{D})$ with ring of integers O_D we let σ denote the automorphism of order 2 obtained by sending $\sqrt{D}$ to $-\sqrt{D}$. Theorem (2.6) is the analogon of Theorem (2.1).

(2.6) **Theorem.** *Let* $n = h \cdot 2^k - 1$ *with* $0 < h < 2^k$ *and* h *odd. Suppose there exist* $D \equiv 0, 1 \mod 4$, *and* $\alpha \in O_D$, *such that* $(\frac{D}{n}) = -1$ *and* $(\frac{\mathrm{N}(\alpha)}{n}) = -1$. *Then*

$$n \text{ is prime} \Longleftrightarrow \left(\frac{\alpha}{\sigma\alpha}\right)^{(n+1)/2} \equiv -1 \mod n. \tag{2.7}$$

The way Theorem (2.6) is used for an explicit primality test for $h \cdot 2^k - 1$ will be clear: one looks for a pair D and α such that both D and the norm of α have Jacobi symbol -1.

(2.8) **Problem.** Given an odd integer $h > 1$. Determine a finite set $\mathscr{D}$ and for every positive integer $k \geq 2$ a pair $(D, \alpha) \in \mathscr{D} \times O_D$, such that either

$$\left(\frac{D}{h \cdot 2^k - 1}\right) = -1 = \left(\frac{\mathrm{N}(\alpha)}{h \cdot 2^k - 1}\right)$$

or

$$\left(\frac{D}{h \cdot 2^k - 1}\right) = 0 \quad \text{and} \quad D \not\equiv 0 \mod h \cdot 2^k - 1 .$$

(2.9) *Remarks.* As in the previous case, for a solution of (2.8) to be explicit we want the finite set $\mathscr{D}$ together with a map telling which pair to choose for each $k \geq 2$. Solving (2.8) again leads to an explicit primality criterion by (2.6), or a factor. Sometimes we will be sloppily using prime $D \equiv 3 \mod 4$ instead of the associated discriminant $4D$.

It remains to be explained how (2.6) relates to the formulation of the Lucas-Lehmer test (1.2) in the introduction. For that, let $\alpha \in O_D$ and let $\beta = \frac{\alpha}{\sigma\alpha}$. Furthermore, let $e_0 = \beta^h + \beta^{-h}$ and $e_{j+1} = e_j^2 - 2$ for $j \geq 0$. Then, by induction, for $j \geq 0$:

$$e_j = \beta^{h \cdot 2^j} + \beta^{-h \cdot 2^j} .$$

Hence,

$$\begin{aligned} e_{k-2} \equiv 0 \mod n &\iff \beta^{h \cdot 2^{k-2}} + \beta^{-h \cdot 2^{k-2}} \equiv 0 \mod n \\ &\iff \beta^{(n+1)/4} + \beta^{-(n+1)/4} \equiv 0 \mod n \\ &\iff \beta^{(n+1)/2} = -1 \mod n . \end{aligned}$$

Thus, a solution to Problem (2.8) immediately yields a finite generalization of (1.2). Notice that e_0 can itself be deduced from β by a recurrent sequence: if we put $f_0 = 2$ and $f_1 = \beta + \beta^{-1}$, then the relations $f_{j+i} = f_j \cdot f_i - f_{j-i}$ (for $j \geq i$) give $f_j = \beta^j + \beta^{-j}$ for every $j \geq 0$. In particular, $f_{2j} = f_j^2 - 2$ and, importantly, $f_h = \beta^h + \beta^{-h} = e_0$.

Also note that it follows immediately that the starting value e_0 is in fact a rational number, and that its denominator is coprime to n (since it is a divisor of the hth power of $\mathrm{N}(\alpha)$). Thus, one in general obtains a recurrence relation for rational numbers rather than for integers as in the classical Lucas-Lehmer case. Since one is only interested in the values modulo n, multiplying with the inverse of the denominator modulo n yields an integer recurrence relation, but this formulation has as a disadvantage that one ends up with recurrence relations for which the starting value depends on k (not just on α). For an example, see (3.5) below.

3. Special cases

First of all, we deal with the case where h is not divisible by 3.

(3.1) **Theorem.** *Let* $n = h \cdot 2^k + 1$, *with* $h \not\equiv 0 \mod 3$ *and* $k \geq 2$. *Then* $\mathscr{D} = \{3\}$ *and* $D_k = 3$ *(for* $k \geq 2$*) solves Problem* (2.3). *In particular, if* $2^k > h$, *then*

$$n \text{ is prime} \iff 3^{(n-1)/2} \equiv -1 \mod n .$$

Proof. Since $n \equiv 1 \mod 4$, we have $(\frac{3}{n}) = (\frac{n}{3})$. Also, $n = h \cdot 2^k + 1 \equiv 0$ or $2 \mod 3$, and the first assertion is immediate. The second follows by (2.1). □

(3.2) **Theorem.** *Let* $n = h \cdot 2^k - 1$, *with* $n \not\equiv 0 \mod 3$ *and* $k \geq 2$. *Then* $\mathscr{D} = \{12\}$ *and* $(D_k, \alpha_k) = (12, 2 + \sqrt{12})$ *solves Problem* (2.8). *In particular, if* $2^k > h$, *then*

$$n \text{ is prime} \Longleftrightarrow \left(\frac{2+\sqrt{12}}{2-\sqrt{12}}\right)^{(n+1)/2} \equiv -1 \mod n \Longleftrightarrow e_{k-2} \equiv 0 \mod n,$$

where $e_0 = -((2+\sqrt{3})^h + (2-\sqrt{3})^h)$ *and* $e_{j+1} = e_j^2 - 2$ *for* $j \geq 0$.

Proof. $\mathrm{N}(\alpha) = (2+\sqrt{12})(2-\sqrt{12}) = -8$, and therefore, for $k \geq 2$,

$$\left(\frac{12}{n}\right) = -\left(\frac{h \cdot 2^k - 1}{3}\right) = \begin{cases} 0 & \text{if } h \cdot 2^k \equiv 1 \bmod 3, \\ -1 & \text{if } h \cdot 2^k \equiv 2 \bmod 3, \end{cases}$$

using quadratic reciprocity and the fact that $n = h \cdot 2^k - 1 \equiv 3 \mod 4$. Also, if $k \geq 3$, then $n \equiv 7 \mod 8$, and hence

$$\left(\frac{\mathrm{N}(\alpha)}{n}\right) = \left(\frac{-2}{n}\right) = -1.$$

This proves the first assertion.

Using the notation of (2.9), we have

$$\begin{aligned} e_0 = f_h = \beta^h + \beta^{-h} &= \left(\frac{2+\sqrt{12}}{2-\sqrt{12}}\right)^h + \left(\frac{2-\sqrt{12}}{2+\sqrt{12}}\right)^h \\ &= -\left((2+\sqrt{3})^h + (2-\sqrt{3})^h\right), \end{aligned}$$

and the other assertions follow from (2.6) and (2.9). □

Note that (3.1) and (3.2) include the classical case $h = 1$ quoted in the introduction. Of course, much more is known for numbers $2^k \pm 1$, but we are not interested in that here.

We would like to know whether we can generalize (3.1) and (3.2) for h divisible by 3. Not much seems to be known for that case [1, 10, 11]. In general, it will certainly not be possible to use the same D for every k, but it might be possible to use only *finitely many* different values.

The first observation we make is that a solution to Problem (2.3) for one particular h will in general lead to a solution for every h' in the same residue class modulo $\prod_{D \in \mathscr{D}} D$. In that light, (3.1) is in fact a consequence of (1.1) and the special case $h = 5$ and $\mathscr{D} = \{3\}$.

Similarly, a solution for Problem (2.8) for some h will lead to solutions for all h in some residue class with respect to a modulus depending on the D and the norms $\mathrm{N}(\alpha)$ for the pairs (D, α) used.

Next we show that for $h = 4^m - 1$, finite generalizations of (3.1) and (3.2) do not exist.

(3.3) **Theorem.** *Let* $m \geq 1$. *For every finite set* $\mathscr{D} \subset \mathbf{Z}$ *there exist* $k \geq 2$ *such that*

$$\left(\frac{D}{(4^m - 1) \cdot 2^k + 1}\right) = 1 \quad \textit{for every } D \in \mathscr{D}.$$

In other words, Problem (2.3) *does not have a finite solution for* $h = 4^m - 1$.

Proof. Let $\mathscr{D}$ be a finite set. Let $\mathscr{P}$ be the finite set of prime numbers dividing at least one $D \in \mathscr{D}$:

$$\mathscr{P} = \{p | p \text{ prime}, \exists D \in \mathscr{D} : p | D\}.$$

By multiplicativity of the Jacobi symbol, it suffices to prove that there exists $k \geq 2$ such that

$$\left(\frac{p}{(4^m - 1) \cdot 2^k + 1}\right) = 1$$

for every p in $\mathscr{P}$. To do so, simply choose $k \geq 2$ such that k is a multiple of $\mathrm{ord}_p(2)$ for every odd $p \in \mathscr{P}$, where $\mathrm{ord}_p(2)$ denotes the multiplicative order of 2 modulo p. Then

$$\left(\frac{p}{(4^m - 1) \cdot 2^k + 1}\right) = \left(\frac{(4^m - 1) \cdot 1 + 1}{p}\right) = \left(\frac{4^{-m}}{p}\right) = 1.$$

If necessary, we also take $k \geq 3$, so that $(4^m - 1) \cdot 2^k + 1 \equiv +1 \mod 8$ to ensure that

$$\left(\frac{2}{(4^m - 1) \cdot 2^k + 1}\right) = 1.$$

This proves (3.3). □

(3.4) **Theorem.** *Let* $m \geq 1$. *For every finite set* $\mathscr{D}$ *of pairs* (D, α), *with* $D \equiv 0, 1 \mod 4$ *and* $\alpha \in O_D$, *there exist* $k \geq 2$ *such that for every* $(D, \alpha) \in \mathscr{D}$

$$\left(\frac{D}{(4^m - 1) \cdot 2^k - 1}\right) = 1 \quad or \quad \left(\frac{\mathrm{N}(\alpha)}{(4^m - 1) \cdot 2^k - 1}\right) = 1.$$

In other words, Problem (2.8) *does not have a finite solution for* $h = 4^m - 1$.

Proof. Let $\mathscr{D}$ be a finite set of pairs as in the statement of the theorem. Note that of the pair of integers D and $\mathrm{N}(\alpha)$ at least one is positive. Let $\mathscr{P}$ be the finite set of all prime numbers dividing the positive D's and the positive norms $\mathrm{N}(\alpha)$, and $(D, \alpha) \in \mathscr{D}$:

$$\mathscr{P} = \{p | p \text{ prime}, \exists (D, \alpha) \in \mathscr{D} : (D > 0 \text{ and } p | D \text{ or } \mathrm{N}(\alpha) > 0 \text{ and } p | \mathrm{N}(\alpha))\}.$$

By multiplicativity of the Jacobi symbol, it suffices to prove that there exists $k \geq 2$ such that

$$\left(\frac{p}{(4^m - 1) \cdot 2^k - 1}\right) = 1$$

for every p in $\mathscr{P}$. To do so, simply choose $k \geq 2$ such that $k \equiv -2m \mod \mathrm{ord}_p(2)$ for every odd $p \in \mathscr{P}$, where $\mathrm{ord}_p(2)$ denotes the multiplicative order of 2 modulo p. Then

$$\begin{aligned}\left(\frac{p}{(4^m - 1) \cdot 2^k - 1}\right) &= \left(\frac{-((4^m - 1) \cdot 2^k - 1)}{p}\right) \\ &= \left(\frac{-((4^m - 1) \cdot 4^{-m} - 1)}{p}\right) = \left(\frac{4^m}{p}\right) = 1.\end{aligned}$$

If necessary, we also take $k \geq 3$ so that $(4^m - 1) \cdot 2^k - 1 \equiv -1 \mod 8$ to ensure that

$$\left(\frac{2}{(4^m - 1) \cdot 2^k - 1}\right) = 1.$$

This proves (3.4). □

(3.5) *Remarks*. The best one could hope for in case $h = 4^m - 1$ is to find infinite sets as in (2.3) and (2.8), parametrized by k. We easily obtained such results for $m = 1, 2$; for example, let $n_k = 3 \cdot 2^k - 1$ for $k \geq 2$, and define

$$(3.6)\quad (D_k, \alpha_k) = \begin{cases} (7, 2+\sqrt{7}) & \text{if } k \equiv 0, 2 \mod 3, \\ (73, 3+\sqrt{73}) & \text{if } k \equiv 1, 4 \mod 9, \\ (2^{(k-1)/3}+1, 1+\sqrt{2^{(k-1)/3}+1}) & \text{if } k \equiv 7 \mod 9. \end{cases}$$

Then $(\frac{D_k}{n_k}) = -1 = (\frac{\mathrm{N}(\alpha_k)}{n_k})$ for every $k \geq 1$; furthermore,

$$n_k \text{ is prime} \iff \left(\frac{\alpha_k}{\sigma\alpha_k}\right)^{(n_k+1)/2} \equiv -1 \mod n_k .$$

Borho [1] presents a different parametrized infinite solution for (2.8) with $h = 3$. He also gives a parametrized solution for $h = 9$, but as we will see below, for that case a finite solution exists.

As a final example of an explicit primality test in terms of a recurrent sequence we indicate how the first case of (3.6) translates. So let $h = 3$ and $k \equiv 0, 2 \mod 3$. In the notation of (2.9), $\beta = \frac{2+\sqrt{7}}{2-\sqrt{7}}$ and $e_0 = \beta^3 + \beta^{-3} = -\frac{10054}{3^3}$. We have here a denominator 3^3 in the starting value for our recurrent sequence; however, since $n = 3 \cdot 2^k - 1$, one has $3^{-1} \equiv 2^k \mod n$ and (3.6) implies for $k \equiv 0, 2 \mod 3$:

$$n_k \text{ is prime} \iff e_{k-2} \equiv 0 \mod n_k ,$$

where $e_0 = -10054 \cdot 2^{3k}$ and $e_{j+1} = e_j^2 - 2$ for $j > 1$.

4. The general case

The next question is: what happens for $h \equiv 3 \mod 6$ not of the form $4^m - 1$? Although I have not been able to prove it, all the evidence (including all cases for h up to 100000) seems to suggest that for such h there *always* exists a solution of Problems (2.3) and (2.8)!

A natural but naïve first attack to Problem (2.3) consists of finding a suitable D_k for $k = 2, 3, \ldots$ in succession, by using the smallest one that works, and by keeping track of the k for which a given value D works. What is wrong with this approach is that it uses an ordering of the D's according to size, while it is the order of 2 modulo D that is important, because this determines the modulus for the residue classes of k for which D is suitable.

The next attempt, therefore, is to run through the primes D in order of increasing multiplicative order of 2 in $(\mathbf{Z}/D\mathbf{Z})^*$. This resulted in the first algorithm that we tried out in practice, by writing a very short program in the Cayley language [4]. We used a table of the complete factorizations of all integers $2^u - 1$ for $2 \leq u \leq U = 250$, obtained from [3] and direct factorization in Cayley.

This worked in fact so well, that we tried it for every $h \equiv 3 \mod 6$ up to 10000. Out of the 1667 positive such h less than 10000, six are of the form $4^m - 1$, and only 36 others were not dealt with by this algorithm.

To deal with the remaining cases, one could try to increase the bound U, but for that we would have to overcome the difficulties of factoring $2^u - 1$ for large

u, which would soon become unfeasible. Instead, we have tried to predict for *which* values of u we might be successful. It turns out that the main problem lies in the possibility that $n = h \cdot 2^k + 1$ is a square.

(4.1) **Example.** Let $h = 33$; this is the smallest h for which our first algorithm failed. We show in this example that squares form a problem.

If we list the factorizations of $n_k = 33 \cdot 2^k + 1$ for the first few values of k, one notices that n_k is the square of an integer for $k = 4$ and $k = 7$: indeed $n_4 = 33 \cdot 2^4 + 1 = 23^2$ and $n_7 = 33 \cdot 2^7 + 1 = 5^2 \cdot 13^2$. Therefore, the *only* $D > 1$ for which $(\frac{D}{n_4}) \neq 1$ is $D = 23$. Since the order of 2 modulo D is 11, this forces us to consider residue classes modulo 11. For n_7 we may use $D = 5$, so already we need to consider k modulo 44 because of these squares. In fact, these two are the only squares among $n_k = 33 \cdot 2^k + 1$ for $k \geq 1$ (this will follow from the proposition below).

However, even if n_k is not a square, it may be that $(\frac{D}{n_k}) = 1$ for every finite set of primes D not dividing some integer b, for all k in a residue class with respect to some modulus. This happens in case $h + 2^k$ is a square. In this example, take for instance $b = 34$, and define for any finite set $\mathscr{D}$ of primes not dividing b the integer k by $k \equiv -8 \bmod \mathrm{ord}_2(D)$ for every $D \in \mathscr{D}$. Then

$$\left(\frac{D}{33 \cdot 2^k + 1}\right) = \left(\frac{33 \cdot 2^k + 1}{D}\right) = \left(\frac{(2^5 + 1) \cdot 2^{-8} + 1}{D}\right) = \left(\frac{(2^{-4}(1 + 2^4))^2}{D}\right),$$

which equals 1. As a consequence, for every $\mathscr{D}$ we will be stuck with the residue class for $k \equiv -8 \bmod u$, for some modulus u, unless we include $D = 1 + 2^4 = 17$; that forces u to be divisible by 8. Similarly, we will need $D = 7$ (and hence u a multiple of 3) to deal with the case $k \equiv -4$.

These considerations lead us to consider k modulo 264 for $h = 33$. It turns out that the primes contained in $\mathscr{P}_{264}$, the set of divisors of $2^{264} - 1$, do indeed solve Problem (2.3) for $h = 33$; in fact, we do not need a primitive divisor of $2^{264} - 1$ for this, and hence we were able to solve the problem for $h = 33$ without extra factorizations!

The following proposition shows that it is very easy to detect the squares; we will use it to predict what the modulus u will be. Since for $h \cdot 2^k - 1$ we will use basically the same strategy, we deal with that case here at the same time.

(4.2) **Proposition.** (i) *Let $n = h \cdot 2^k + 1$ for some odd $h \geq 1$ and some $k \geq 2$. Then n is a square in $\mathbf{Z}$ if and only if there exists an odd positive integer f such that $h = f \cdot (f \cdot 2^{k-2} \pm 1)$.*

(ii) *Let $n = h + 2^k$ for some odd $h \geq 1$ that is divisible by* 3, *and some $k \geq 2$. Then n is a square in $\mathbf{Z}$ if and only if k is even and there exists an odd positive integer f such that $h = f \cdot (2^{k/2+1} + f)$.*

(iii) *Let $n = h \cdot 2^k - 1$ for some odd $h \geq 1$ and some $k \geq 2$. Then n is never a square in $\mathbf{Z}$.*

(iv) *Let $n = 2^k - h$ for some odd $h \geq 1$ that is divisible by* 3, *and some $k \geq 2$. Then n is a square in $\mathbf{Z}$ if and only if k is even and there exists an odd positive integer f such that $h = f \cdot (2^{k/2+1} - f)$.*

Proof. (i) Suppose that $n = h \cdot 2^k + 1 = d^2$, with d some positive odd integer. Then $d^2 - 1 = h \cdot 2^k$ and $d = f \cdot 2^{k-1} \pm 1$ for some odd f. Thus, $h \cdot 2^k = (d-1)(d+1) = 2^k(f^2 2^{k-2} \pm f)$, from which the assertion follows.

Conversely, if $h = f \cdot (f \cdot 2^{k-2} \pm 1)$, then $n = f \cdot (f \cdot 2^{k-2} + 1) \cdot 2^k + 1 = (f \cdot 2^{k-1} \pm 1)^2$.

(ii) Suppose that $n = h + 2^k = d^2$, with d a positive odd integer. Looking modulo 3, we find that k must be even, say $k = 2l$. Let $f \in \mathbf{Z}$ be such that $d = f + 2^l$; note that f must be odd and positive. Then $d^2 = f^2 + f2^{l+1} + 2^{2l} = h + 2^{2l}$, and, therefore, $h = f^2 + f2^{l+1}$, whence the assertion follows.

Conversely, if $h = f^2 + f \cdot 2^{k/2+1}$, then $h + 2^k = f^2 + f2^{k/2+1} + 2^k = (f + 2^{k/2})^2$.

(iii) Since $h \cdot 2^k - 1 \equiv 3 \bmod 4$ for $k \geq 2$, it cannot be a square.

(iv) Suppose that $n = 2^k - h = d^2$, with d a positive odd integer. Looking modulo 3, we find that k must be even, say $k = 2l$. Let $f \in \mathbf{Z}$ be such that $d = 2^l - f$; note that f must be odd and positive. Then $d^2 = 2^{2l} - f2^{l+1} + f^2 = 2^{2l} - h$, and, therefore, $h = f2^{l+1} - f^2 = f \cdot (2^{k/2+1} - f)$.

Conversely, if $h = f \cdot (2^{k/2+1} - f)$, then $2^k - h = 2^k - f2^{k/2+1} + f^2 = (2^{k/2} - f)^2$. This ends the proof of (4.2). □

(4.3) **Algorithm.**

Input. An integer $h \equiv 3 \bmod 6$, an integer $U > 1$, and for all $2 \leq u \leq U$ a set $\mathscr{P}_u$ consisting of divisors of $2^u - 1$.

Output. A positive integer $r \leq U$ and a sequence of integers $\mathscr{C} = (C_1, C_2, \dots, C_r)$ of length r such that

$$\left(\frac{C_i}{h \cdot 2^k + 1}\right) \neq 1,$$

for every $k \equiv i \bmod r$, with $k \geq 3$.

(1) Find a multiplier $m \geq 1$ which is a positive integer with the property that if $h \cdot 2^k + 1$ is a square, then $\gcd(2^m - 1, h \cdot 2^k + 1) > 1$, and if $h + 2^k$ is a square, then $\gcd(2^m - 1, h + 2^k) > 1$, for every positive integer k.

(2) Put $r = 1$, $u = m$, $\mathscr{R} = \varnothing$, and $\mathscr{C} = (0)$. Repeat the following steps until termination.

(a) Let k be the smallest integer in $3 \leq k \leq r + 2$ such that $k \notin \mathscr{R}$.

(b) If there does not exist $D \in \mathscr{P}_u$ such that

$$\left(\frac{D}{h \cdot 2^k + 1}\right) \neq 1,$$

proceed to step (c); else let D be the smallest such value, let $r' = \operatorname{lcm}(r, u)$, replace $\mathscr{R}$ by

$$\{3 \leq i \leq r' + 2 | i \equiv k \bmod u \text{ or } i \equiv d \bmod r \text{ for some } d \in \mathscr{R}\};$$

replace $\mathscr{C}$ by $(C_1', \dots, C_{r'}')$, where

$$C_i' = \begin{cases} C_j & \text{if } C_j \neq 0, \text{ where } j \equiv i \bmod r, \\ D & \text{if } j \equiv k \bmod r', \\ 0 & \text{otherwise;} \end{cases}$$

next replace r by r'.

(c) Terminate and return $\mathscr{C}$ if either $\#\mathscr{R} = r$ or $u > U - m$. In all other cases: increase u by m.

(4.4) *Remarks.* The sequence returned by Algorithm (4.3) represents a solution to Problem (2.3) if it does not contain a zero entry, that is, if it terminated in step (2)(c) with $\#\mathscr{R} = r$.

In the cases I have considered, h was sufficiently small to allow complete factorization without effort, and inspection of all possible factorizations to obtain the multiplier m, using the above proposition. Alternatively, one could check all of the finitely many possible k that yield squares.

Of course $2^{mu}-1$ is soon too big to be factored completely; if that happened, all known prime factors were used, as well as (very occasionally) composite factors (in particular, divisors of the form $2^d - 1$ of $2^{mu} - 1$, with d a divisor of mu).

Our strategy for attempting to solve Problem (2.8) for $h \cdot 2^k - 1$ is much the same as that employed in Algorithm (4.3) for $h \cdot 2^k + 1$, except that we have to build in an extra step to find a suitable element. We describe this subalgorithm first.

(4.5) **Algorithm.**

Input. An integer $h \equiv 3 \bmod 6$, positive integers k and r, as well as a prime D.

Output. Either an element $\alpha \in O_D$ such that

$$\left(\frac{\mathrm{N}(\alpha)}{h \cdot 2^j - 1}\right) \equiv -1$$

for every $j \equiv k \bmod r$, or 0.

(1) If $D \equiv 1 \bmod 4$, solve $x^2 + y^2 = D$, and return $\alpha = x + \sqrt{D}$.

(2) Choose a suitable bound b, and perform step (a) for pairs x, y with $0 \leq y \leq b$ and $0 \leq x \leq y\sqrt{D}$ (but x, y not both 0) until it is successful, in which case α is returned, or the pairs are exhausted without success, in which case 0 is returned.

(a) Let the integer g coprime to 6 be determined by $x^2 - y^2 D = -2^\delta 3^\varepsilon g$, with δ, $\varepsilon \geq 0$. This step is successful if g is a square or

$$\left(\frac{g}{h \cdot 2^k - 1}\right) = 1 \quad \text{and} \quad \mathrm{ord}_2(g) | r; \tag{4.6}$$

then $\alpha = x + y\sqrt{D}$.

(4.7) *Remarks.* We briefly comment on Algorithm (4.5) which will be used below to find a suitable element α, once D has been found. The search for solutions will be organized in such a way that D will always be positive (recall that either D or $\mathrm{N}(\alpha)$ has to be positive) and usually prime (except that it should be replaced by $4D$ if $D \equiv 2, 3 \bmod 4$). Since $h \cdot 2^k - 1 \equiv 7 \bmod 8$ and $h \cdot 2^k - 1 \equiv 2 \bmod 3$,

$$\left(\frac{-1}{h \cdot 2^k - 1}\right) = -1 \quad \text{and} \quad \left(\frac{2}{h \cdot 2^k - 1}\right) = 1 = \left(\frac{3}{h \cdot 2^k - 1}\right).$$

That means not only that $D = 8$ and $D = 12$ will be unsuitable, but also that any factors 2 and 3 in $\mathrm{N}(\alpha)$ can be ignored, and that $\mathrm{N}(\alpha) = -s^2$ will always be a suitable value. That explains most of step (2) above; the condition given by (4.6) ensures that $\mathrm{N}(\alpha)$ not only works for the current value of k, but in fact for the whole residue class of k modulo the current modulus r.

It is well known that every prime $p \equiv 1 \bmod 4$ can be written in the form $p = x^2 + y^2$. In step (1) this is used: if $D = x^2 + y^2$, then $\mathrm{N}(x + \sqrt{D}) = x^2 - D = -y^2$, hence suitable! Of course, we should explain how to *obtain* x and y to make everything explicit. There are several methods for solving this problem, some of which work very well in practice, even if D gets big (in our calculations we used D of up to 106 decimal digits). One method is to find the square root of -1 modulo D and recover x and y from such root. We refer the reader to [8, 5] and the references therein for details about these algorithms.

For prime $D \equiv 3 \bmod 4$ such a general solution does not exist. Still, in step (2) of the above algorithm one will often still find a suitable solution, particularly for small D. We give a few examples in Table 0.

Table 0 contains for certain prime $D \equiv 3 \bmod 4$ less than 100 an element α such that $\mathrm{N}(\alpha) = -2^\delta 3^\varepsilon$ as found from Algorithm (4.5) with bound $b = 25$ on y. It shows that such a solution (which is suitable for any h and k) was found for every such D with the exception of $D = 23$, 47, 71. (It is of course no coincidence that for $D \equiv 23 \bmod 24$ no solution was found: it is easy to see that for these we are trying to solve $x^2 - Dy^2 = -s^2$ or $x^2 - Dy^2 = -2s^2$, which is impossible.) Note that $2^\delta 3^\varepsilon$ may appear in the denominator of the starting value e_0 as in (2.9) and (3.5).

TABLE 0

D	α	$\mathrm{N}(\alpha)$
7	$2+\sqrt{7}$	-3
11	$3+\sqrt{11}$	-2
19	$4+\sqrt{19}$	-3
31	$2+\sqrt{31}$	-27
43	$4+\sqrt{43}$	-27
59	$23+3\sqrt{59}$	-2
67	$7+\sqrt{67}$	-18
79	$5+\sqrt{79}$	-54

Still, $D = 23$ (or 47 or 71) may be useful in combination with an element that only works for particular h and k; such a value is sought after in the last part of the algorithm. For instance, with $h = 33$, let $k = 8$; then

$$\left(\frac{23}{33\cdot 2^8 - 1}\right) = -1 = \left(\frac{-14}{33\cdot 2^8 - 1}\right) = \left(\frac{\mathrm{N}(3+\sqrt{23})}{33\cdot 2^8 - 1}\right).$$

Since the order $\mathrm{ord}_7(2) = 3$, the element $3+\sqrt{23}$ is suitable for all $k \equiv 8 \bmod r$ if this current modulus r is a multiple of 3.

(4.8) **Algorithm.**

Input. A positive integer $h \equiv 3 \bmod 6$, an integer $U > 1$, and for all $2 \le u \le U$ a set $\mathscr{P}_u$ consisting of divisors of $2^u - 1$.

Output. A positive integer $r \le U$ and a sequence $\mathscr{C} = ((D_1, \alpha_1), (D_2, \alpha_2), \ldots, (D_r, \alpha_r))$ of length $r \le U$, with integers $0 < D_i \equiv 0,\ 1 \bmod 4$ and

$\alpha_i \in O_{D_i}$, such that

$$\left(\frac{D_i}{h \cdot 2^k - 1}\right) \neq 1 \quad \text{and} \quad \left(\frac{\mathrm{N}(\alpha_i)}{h \cdot 2^k - 1}\right) \neq 1$$

for every $k \equiv i \bmod r$ (with $k \geq 2$).

(1) Find a multiplier m, which is a positive integer with the property that if $2^k - h$ is a square, then $\gcd(2^m - 1, 2^k - h) > 1$ for every positive integer k.

(2) Put $r = 1$, $\mathscr{R} = \varnothing$, $u = m$, and $\mathscr{C} = ((0, 0))$. Repeat the following steps until termination.

(a) Let k be the smallest integer in $3 \leq k \leq r + 2$ such that $k \notin \mathscr{R}$.

(b) If there exists no $D \in \mathscr{P}_u$ such that

$$\left(\frac{D}{h \cdot 2^k + 1}\right) \neq 1$$

then proceed to step (c); else, let D be the smallest value satisfying this, let $r' = \operatorname{lcm}(r, u)$, and perform Algorithm (4.5) with h, k, r', and D to find an element α. If $\alpha = 0$, proceed to step (c); else replace $\mathscr{R}$ by

$$\{3 \leq i \leq r' + 2 | i \equiv k \bmod u \text{ or } i \equiv d \bmod r \text{ for some } d \in \mathscr{R}\};$$

replace $\mathscr{C}$ by $((D_1, \alpha_1)', \dots, (D_{r'}, \alpha_{r'})')$, where

$$(D_j, \alpha_j)' = \begin{cases} (D_i, \alpha_i) & \text{if } (D_i, \alpha_i) \neq (0, 0), \text{ where } j \equiv i \bmod r, \\ (D, \alpha) & \text{if } j \equiv k \bmod r', \\ (0, 0) & \text{otherwise}; \end{cases}$$

next replace r by r'.

(c) Terminate and return the sequence $\mathscr{C}$ if either $\#\mathscr{R} = r$ or $u > U - m$. In all other cases: increase u by m.

The sequence returned by Algorithm (4.8) represents a solution to Problem (2.8) for h if it does not contain entries of the form $(0, 0)$, that is, if it terminated in step (2)(c) with $\#\mathscr{R} = r$.

(4.9) **Numerical results.** Six tables (see the Supplement at the end of this issue) summarize the results of running our Cayley implementations of Algorithms (4.3) and (4.8) for h up to 10^5. In these tables, m signifies the multiplier found in step (1) to trap a factor for every possible square, and r denotes the modulus ('period') for the explicit primality test, as returned by the algorithms. Subscripts $+$ and $-$ indicates tests for $h \cdot 2^k + 1$ and $h \cdot 2^k - 1$.

In Table 1 multipliers and periods are shown, found using (4.3) for all $h \equiv 3 \bmod 6$ with $h < 1000$. Tables 2 and 3 show the hardest cases for h up to 100000: in Table 2 all cases for which r_+ is at least 50 times m_+ are listed, and Table 3 shows all cases where $m_+ \geq 500$. The largest period found was just over 100000.

Tables 4–6 show the corresponding results obtained with Algorithm (4.8), but Table 6 lists all cases with $m_- \geq 100$. The largest period encountered is over half a million.

Notice in the tables that the period r is *not* always an integral multiple of the multiplier m; the reason for this is that a solution found with r a multiple of m sometimes shows an 'accidental' periodicity with modulus a divisor of r that is not a multiple of m.

Finally, we explicitly describe the solutions for $h = 9$ implied by our calculations. According to Table 1, there exists a solution for $9 \cdot 2^k + 1$ with $r = 24$ (and $m = 8$, because the squares $9 + 2^4 = 5^2$ and $9 \cdot 2^5 + 1 = 17^2$ are trapped by $2^8 - 1 = 3 \cdot 5 \cdot 17$), and by Table 4 there is a solution for $9 \cdot 2^k - 1$ with $r = 4$.

(4.10) **Theorem.** *Let* $n_k = 9 \cdot 2^k + 1$ *and define* $D_k \in \{5, 7, 17, 241\}$ *for* $k \geq 2$ *as follows*:

$$D_k = \begin{cases} 5 & \text{if } k \equiv 0, 2, 3 \bmod 4, \\ 7 & \text{if } k \equiv 1, 9, 13, 21 \bmod 24, \\ 17 & \text{if } k \equiv 5 \bmod 24, \\ 241 & \text{if } k \equiv 17 \bmod 24. \end{cases}$$

Then $(\frac{D_k}{n_k}) \neq 1$ *for* $k \geq 2$. *Hence, if* $k \geq 4$, *then*

$$n_k \text{ is prime} \iff D_k^{(n_k-1)/2} \equiv -1 \mod n_k.$$

(4.11) **Theorem.** *Let* $n_k = 9 \cdot 2^k - 1$ *and define* D_k, α_k *for* $k \geq 2$ *by*

$$(D_k, \alpha_k) = \begin{cases} (5, 1 + \sqrt{5}) & \text{if } k \equiv 0, 1, 2 \bmod 4, \\ (17, 1 + \sqrt{17}) & \text{if } k \equiv 3 \bmod 4. \end{cases}$$

Then $(\frac{D_k}{n_k}) \neq 1$ *and* $(\frac{\mathrm{N}(\alpha_k)}{n_k}) = -1$ *for every* $k \geq 2$. *Hence, if* $k \geq 4$, *then*

$$n_k \text{ is prime} \iff \left(\frac{\alpha_k}{\sigma\alpha_k}\right)^{(n_k+1)/2} \equiv -1 \mod n_k.$$

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