All bi-unitary perfect polynomials over $\mathbb{F}_2$ with at most four irreducible factors

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Abstract
We give, in this paper, all bi-unitary perfect polynomials over the prime field $\mathbb{F}_2$, with at most four irreducible factors.

1 Introduction

Let $S \in \mathbb{F}_2[x]$ be a nonzero polynomial. We say that S is odd if $\gcd(S, x(x+1)) = 1$, S is even if it is not odd. A *Mersenne* (*prime*) is a polynomial (irreducible) of the form $1 + x^a(x+1)^b$, with $\gcd(a, b) = 1$. A divisor D of S is called unitary if $\gcd(D, S/D) = 1$. We denote by $\gcd_u(S, T)$ the greatest common unitary divisor of S and T. A divisor D of S is called bi-unitary if $\gcd_u(D, S/D) = 1$.
We denote by $\sigma(S)$ (resp. $\sigma^*(S)$, $\sigma^{**}(S)$) the sum of all divisors (resp. unitary divisors, bi-unitary divisors) of S. The functions σ, σ^* and σ^{**} are all multiplicative. We say that a polynomial S is *perfect* (resp. *unitary perfect*, *bi-unitary perfect*) if $\sigma(S) = S$ (resp. $\sigma^*(S) = S$, $\sigma^{**}(S) = S$).
Finally, we say that S is *indecomposable bi-unitary perfect* (*i.b.u.p.*) if it is bi-unitary perfect but it is not a product of two coprime nonconstant bi-unitary perfect polynomials.
As usual, $\omega(S)$ designates the number of distinct irreducible factors of S.
Several studies are done about perfect and unitary perfect. In particular, we gave ([3], [4], [5]) the list of all (unitary) perfect polynomials A over $\mathbb{F}_2$ (even or not), with $\omega(A) \leq 4$.

In this paper, we are interested in bi-unitary perfect polynomials (b.u.p. polynomials) A with $\omega(A) \leq 4$. If $A \in \mathbb{F}_2[x]$ is nonconstant b.u.p., then $x(x+1)$ divides A so that $\omega(A) \geq 2$ (see Lemma 2.5). Moreover, the only b.u.p. polynomials over $\mathbb{F}_2$ with exactly two prime factors are $x^2(x+1)^2$ and $x^{2^n-1}(x+1)^{2^n-1}$, for any nonnegative integer n ([1], Theorem 5). We prove (Theorems 1.1 and 1.2) that the only b.u.p. polynomials $A \in \mathbb{F}_2$, with $\omega(A) \in \{3, 4\}$, are those given in [1], plus four other ones. Note that all odd irreducible divisors of the C_j's are Mersenne primes (there is a misprint for C_6, in [1]).

In the rest of the paper, for $S \in \mathbb{F}_2[x]$, we denote by $\overline{S}$ the polynomial obtained from S with x replaced by $x+1$: $\overline{S}(x) = S(x+1)$.
As usual, $\mathbb{N}$ (resp. $\mathbb{N}^*$) denotes the set of nonnegative integers (resp. of positive integers).
For $S, T \in \mathbb{F}_2[x]$ and $n \in \mathbb{N}^*$, we write: $S^n \| T$ if $S^n | T$ but $S^{n+1} \nmid T$.
Finally, let $\mathcal{M}$ denotes the set of all Mersenne primes.

We consider the following polynomials over $\mathbb{F}_2$:

$M_1 = 1+x+x^2 = \sigma(x^2),\ M_2 = 1+x+x^3,\ M_3 = \overline{M_2} = 1+x^2+x^3,$
$M_4 = 1+x+x^2+x^3+x^4 = \sigma(x^4), M_5 = \overline{M_4} = 1+x^3+x^4,$
$S_1 = 1+x(x+1)M_1 = 1+x+x^4,$
$C_1 = x^3(x+1)^4M_1, C_2 = x^3(x+1)^5{M_1}^2, C_3 = x^4(x+1)^4{M_1}^2,$
$C_4 = x^6(x+1)^6{M_1}^2, C_5 = x^4(x+1)^5{M_1}^3, C_6 = x^7(x+1)^8M_5,$
$C_7 = x^7(x+1)^9{M_5}^2, C_8 = x^8(x+1)^8M_4M_5, C_9 = x^8(x+1)^9M_4{M_5}^2,$
$C_{10} = x^7(x+1)^{10}{M_1}^2M_5, C_{11} = x^7(x+1)^{13}{M_2}^2{M_3}^2,$
$C_{12} = x^9(x+1)^9{M_4}^2{M_5}^2, C_{13} = x^{14}(x+1)^{14}{M_2}^2{M_3}^2,$
$D_1 = x^4(x+1)^5{M_1}^4S_1, D_2 = x^4(x+1)^5{M_1}^5{S_1}^2.$
The polynomials $M_1, \ldots, M_5 \in \mathcal{M}$. We set $\mathcal{U} := \{M_1, \ldots, M_5\}$.

Theorem 1.1. *Let $A \in \mathbb{F}_2[x]$ be b.u.p. such that $\omega(A) = 3$. Then $A, \overline{A} \in \{C_j : j \leq 7\}$.*

Theorem 1.2. *Let $A \in \mathbb{F}_2[x]$ be b.u.p. such that $\omega(A) = 4$. Then $A, \overline{A} \in \{C_j : 8 \leq j \leq 13\} \cup \{D_1, D_2\}$.*

2 Preliminaries

We need the following results. Some of them are obvious or (well) known, so we omit their proofs.

Lemma 2.1. *Let T be an irreducible polynomial over $\mathbb{F}_2$ and $k, l \in \mathbb{N}^*$. Then, $\gcd_u(T^k, T^l) = 1$ (resp. T^k) if $k \neq l$ (resp. $k = l$).*
In particular, $\gcd_u(T^k, T^{2n-k}) = 1$ for $k \neq n$, $\gcd_u(T^k, T^{2n+1-k}) = 1$ for any $0 \leq k \leq 2n+1$.

Lemma 2.2. *Let $T \in \mathbb{F}_2[x]$ be irreducible. Then*
i) $\sigma^{**}(T^{2n}) = (1+T)\sigma(T^n)\sigma(T^{n-1}),\ \sigma^{**}(T^{2n+1}) = \sigma(T^{2n+1})$.
ii) For any $c \in \mathbb{N}$, T does not divide $\sigma^{**}(T^c)$.

Proof. i): $\sigma^{**}(T^{2n}) = 1+T+\cdots+T^{n-1}+T^{n+1}+\cdots+T^{2n} = (1+T^{n+1})\sigma(T^{n-1}) = (1+T)\sigma(T^n)\sigma(T^{n-1})$, $\sigma^{**}(T^{2n+1}) = 1+T+\cdots+T^{2n+1}$.
ii) follows from i). □

Corollary 2.3. *Let $T \in \mathbb{F}_2[x]$ be irreducible. Then*
i) If $a \in \{4r, 4r+2\}$, where $2r-1$ or $2r+1$ is of the form $2^\alpha u - 1$, u odd, then $\sigma^{**}(T^a) = (1+T)^{2^\alpha} \cdot \sigma(T^{2r}) \cdot (\sigma(T^{u-1}))^{2^\alpha},\ \gcd(\sigma(T^{2r}), \sigma(T^{u-1})) = 1$.
ii) If $a = 2^\alpha u - 1$ is odd, with u odd, then $\sigma^{**}(T^a) = (1+T)^{2^\alpha - 1} \cdot (\sigma(T^{u-1}))^{2^\alpha}$.

Corollary 2.4. *i) The polynomial $\sigma^{**}(x^a)$ splits over $\mathbb{F}_2$ if and only if $a = 2$ or $a = 2^\alpha - 1$, for some $\alpha \in \mathbb{N}^*$.*
ii) Let $T \in \mathbb{F}_2[x]$ be odd and irreducible. Then $\sigma^{**}(T^c)$ splits over $\mathbb{F}_2$ if and only if (T is Mersenne, $c = 2$ or $c = 2^\gamma - 1$ for some $\gamma \in \mathbb{N}^*$).

Lemma 2.5. *If A is a nonconstant b.u.p. polynomial over $\mathbb{F}_2$, then $x(x+1)$ divides A so that $\omega(A) \geq 2$.*

Lemma 2.6. *If $A = A_1A_2$ is b.u.p. over $\mathbb{F}_2$ and if $\gcd(A_1, A_2) = 1$, then A_1 is b.u.p. if and only if A_2 is b.u.p.*

Lemma 2.7. *If A is b.u.p. over $\mathbb{F}_2$, then the polynomial $\overline{A}$ is also b.u.p. over $\mathbb{F}_2$.*

Lemma 2.8 below gives some useful results from Canaday's paper ([2], Lemmas 4, 5, 6, Theorem 8 and Corollary on page 728).

Lemma 2.8. *Let $P, Q \in \mathbb{F}_2[x]$ be such that P is irreducible and let $n, m \in \mathbb{N}$.*
i) *If $\sigma(P^{2n}) = Q^m$, then $m \in \{0, 1\}$.*
ii) *If $\sigma(P^{2n}) = Q^mT$, with $m > 1$ and $T \in \mathbb{F}_2[x]$ is nonconstant, then* $\deg(P) > \deg(Q)$.
iii) *If P is a Mersenne prime and if $P = P^*$, then $P \in \{M_1, M_4\}$.*
iv) *If $\sigma(x^{2n}) = PQ$ and $P = \sigma((x+1)^{2m})$, then $2n = 8$, $2m = 2$, $P = M_1$ and $Q = P(x^3) = 1 + x^3 + x^6$.*
v) *If any irreducible factor of $\sigma(x^{2n})$ is a Mersenne prime, then $2n \leq 6$.*
vi) *If $\sigma(x^{2n})$ is a Mersenne prime, then $2n \in \{2, 4\}$.*
vii) *If $\sigma(x^n) = \sigma((x+1)^n)$, then $n = 2^h - 2$, for some $h \in \mathbb{N}^*$.*

Lemma 2.9. [see [6], Lemma 2.6] *Let $m \in \mathbb{N}^*$ and T be a Mersenne prime. Then, $\sigma(x^{2m})$, $\sigma((x+1)^{2m})$ and $\sigma(M^{2m})$ are all odd and squarefree.*

The following equalities (obtained from Corollary 2.3) are useful.

$$\begin{cases} \sigma^{**}(T^2) = (1+T)^2, \text{ if } T \text{ is irreducible} \\ \\ \text{For } a, b \geq 3, \\ \\ \sigma^{**}(x^a) = (1+x)^{2^\alpha} \cdot \sigma(x^{2r}) \cdot (\sigma(x^{u-1}))^{2^\alpha}, \text{ with } \gcd(\sigma(x^{2r}), \sigma(x^{u-1})) = 1, \\ \text{if } a = 4r, 2r-1 = 2^\alpha u - 1, \text{ (resp. } a = 4r+2, 2r+1 = 2^\alpha u - 1), \ u \text{ odd} \\ \\ \sigma^{**}((x+1)^b) = x^{2^\beta} \cdot \sigma((x+1)^{2s}) \cdot (\sigma((x+1)^{v-1}))^{2^\beta}, \\ \text{if } b = 4s, 2s-1 = 2^\beta v - 1, \text{ (resp. } b = 4s+2, 2s+1 = 2^\beta v - 1), \ v \text{ odd} \\ \\ \sigma^{**}(x^a) = (1+x)^{2^\alpha - 1} \cdot (\sigma(x^{u-1}))^{2^\alpha}, \text{if } a = 2^\alpha u - 1 \text{ is odd, with } u \text{ odd} \\ \sigma^{**}((x+1)^b) = x^{2^\beta - 1} \cdot (\sigma((x+1)^{v-1}))^{2^\beta}, \text{if } b = 2^\beta v - 1 \text{ is odd, with } v \text{ odd} \\ \\ r, \ \alpha, \ \beta \geq 1. \end{cases} \tag{1}$$

Moreover, we shall also (prove and) consider the following relations:

$$c \in \{2, 2^\gamma - 1 : \gamma \geq 1\}, \ \sigma^{**}(P^c) = (1+P)^c \text{ (in Section 3).} \tag{2}$$

In Section 4.1:

$$c, d \in \{2, 2^\gamma - 1 : \gamma \geq 1\}, \ \sigma^{**}(P^c) = (1+P)^c, \ \sigma^{**}(Q^d) = (1+Q)^d \tag{3}$$

and in Section 4.2:

$$\begin{cases} \sigma^{**}(P^c) = (1+P)^{2^\gamma} \cdot \sigma(P^{2t}) \cdot (\sigma(P^{w-1}))^{2^\gamma}, \text{ with } \gcd(\sigma(P^{2t}), \sigma(P^{w-1})) = 1, \\ \text{if } c \in \{4t, 4t+2\}, \text{ where } 2t-1 \text{ or } 2t+1 \text{ is of the form } 2^\gamma w - 1, \ w \text{ odd} \\ \\ \sigma^{**}(P^c) = (1+P)^{2^\gamma - 1} \cdot (\sigma(P^{w-1}))^{2^\gamma}, \text{ if } c = 2^\gamma w - 1 \text{ is odd, with } w \text{ odd} \\ \\ d \in \{2, 2^\gamma - 1 : \gamma \geq 1\}, \ \sigma^{**}(Q^d) = (1+Q)^d = x^{u_2 d}(x+1)^{v_2 d} P^{w_2 d} \\ \\ r, \alpha, \beta, u_2, v_2, w_2 \geq 1, \ \varepsilon_1 = \min(1, u-1), \ \varepsilon_2 = \min(1, v-1), \ \varepsilon_1, \varepsilon_2 \in \{0, 1\}. \end{cases} \tag{4}$$

3 Proof of Theorem 1.1

We set $A = x^a(x+1)^b P^c$, with $a, b, c \in \mathbb{N}^*$ and P odd irreducible.
We suppose that A is b.u.p.:

$$\sigma^{**}(x^a) \cdot \sigma^{**}((x+1)^b) \cdot \sigma^{**}(P^c) = \sigma^{**}(A) = A = x^a(x+1)^b P^c.$$

We show that P is a Mersenne prime. By direct (Maple) computations, we get our result from Lemma 3.4.

Lemma 3.1. *The polynomial $\sigma^{**}(x^a(x+1)^b)$ does not split, so that $(a \geq 3$ or $b \geq 3)$ and $(a \neq 2^n - 1$ or $b \neq 2^m - 1$ for any $n, m \geq 1)$.*

Proof. If $\sigma^{**}(x^a(x+1)^b)$ splits, then $\sigma^{**}(x^a(x+1)^b) = x^b(x+1)^a$. Thus, $a = b$ and $\sigma^{**}(P^c) = P^c$. It contradicts Lemma 2.2-ii).
If $a, b \leq 2$ or $(a = 2^n - 1,\ b = 2^m - 1$ for some $n, m \geq 1)$, then $\sigma^{**}(x^a)$ and $\sigma^{**}((x+1)^b)$ split. □

Corollary 3.2. *The polynomial P is a Mersenne prime, $P \in \{M_1, M_4, M_5\}$. Moreover, $c = 2$ or $c = 2^\gamma - 1$, for some $\gamma \geq 1$ and $c \leq \min(a, b)$.*

Proof. By Lemma 3.1, there exists $m \geq 1$ such that $\sigma(x^{2m})$ or $\sigma((x+1)^{2m})$ divides $\sigma^{**}(A) = A$. Moreover, P does not divide $\sigma^{**}(P^c)$. We conclude that $P \in \{\sigma(x^{2m}), \sigma((x+1)^{2m})\}$. Thus, $2m \leq 4$ by Lemma 2.8-vi). By Corollary 2.4, $\sigma^{**}(P^c)$ must split. So, c takes the expected value. Furthermore, x^c and $(x+1)^c$ both divide $\sigma^{**}(A) = A$, because they divide $(1+P)^c = \sigma^{**}(P^c)$. So, $c \leq \min(a, b)$. □

Lemma 3.3. *If a (resp. b) is even, then $a \geq 4$ (resp. $b \geq 4$).*

Proof. Put $P = 1 + x^{u_1}(x+1)^{v_1}$. If $a = 2$, then $b \geq 3$, $\sigma^{**}(x^a) = (1+x)^2$, $x^2 \| A = \sigma^{**}(A)$. By comparing a with the exponent of x in $\sigma^{**}(A)$, we get $a = 2^\beta + u_1 c > 2$ if b is even, $a = 2^\beta - 1 + u_1 c$ if b is odd, with $b = 2^\beta v - 1$. So, b is odd, $\beta = u_1 = c = 1$. We also have: $P = \sigma((x+1)^{v-1})$ and $c = 2^\beta \geq 2$, which is impossible. □

Lemma 3.4. *i) If a is even, then $a \in \{4, 6, 8, 10\}$ and $c \in \{1, 2, 3, 7\}$.*
ii) If a is even and b odd, then $b \in \{2^\beta v - 1 : v \in \{1, 3, 5\}, \beta \in \{1, 2, 3\}\}$.
iii) If a and b are both odd, then $a, b \in \{1, 3, 5, 7, 9\}$ and $c \in \{1, 2, 3, 7\}$.

Proof. i): Since $a \geq 4$ (Lemma 3.3), put $a = 4r$ or $a = 4r + 2$, with $r \geq 1$. Then, $\sigma(x^{2r})$ divides $\sigma^{**}(A)$. So, $2r \leq 4$ and $c \leq a \leq 10$.
ii): Write $b = 2^\beta v - 1$, where v is odd. Since $\sigma((x+1)^{v-1})$ divides $\sigma^{**}(A) = A$, $v \in \{1, 3, 5\}$ and $2^\beta - 1 \leq a \leq 10$.
iii): Write $a = 2^\alpha u - 1$ and $b = 2^\beta v - 1$, where u, v are odd. As above, $u, v \in \{1, 3, 5\}$. $\sigma^{**}(x^a(x+1)^b)$ does not split, so $u \geq 3$ or $v \geq 3$. Moreover, $\alpha = 1$ (resp. $\beta = 1$) if $u \geq 3$ (resp. $v \geq 3$). We also get: $2^\beta - 1 \leq a,\ 2^\alpha - 1 \leq b$. If $\alpha = 1 = \beta$, then $a, b \leq 9$. If $\alpha = 1$ and $v = 1$, then $b = 2^\beta - 1 \leq a \leq 9$ so that $b \leq 7$. If $u = 1$ and $\beta = 1$, then $a = 2^\alpha - 1 \leq 7$ and $b \leq 9$. □

4 Proof of Theorem 1.2

In this section, we set $A = x^a(x+1)^b P^c Q^d$, with $a, b, c, d \in \mathbb{N}^*$, P, Q odd irreducible, and $\deg(P) \leq \deg(Q)$. We suppose that A is b.u.p.:

$$\sigma^{**}(x^a) \cdot \sigma^{**}((x+1)^b) \cdot \sigma^{**}(P^c) \cdot \sigma^{**}(Q^d) = \sigma^{**}(A) = A = x^a(x+1)^b P^c Q^d.$$

We prove that $P \in \mathcal{M}$ (Lemma 4.1). Moreover, $Q \in \mathcal{M}$ or it is of the form $1 + x^{u_2}(x+1)^{v_2} P^{w_2}$, where $u_2, v_2, w_2 \geq 1$.

Lemma 4.1. *i) The polynomial P is a Mersenne prime.*
ii) The integer d equals 2 or it is of the form $d = 2^\delta - 1$, with $\delta \in \mathbb{N}^*$.
iii) The polynomial Q is of the form $1+x^{u_2}(x+1)^{v_2}P^{w_2}$, where $w_2 \in \{0, 1\}$.
iv) One has: $a, b \geq 3$ and $d \leq \min(a, b)$.
v) If $\sigma^{**}(P^c)$ does not split, then Q is its unique odd divisor.

Proof. i): We remark that $1+P$ divides $\sigma^{**}(P^c)$. If $1+P$ does not split over $\mathbb{F}_2$, then Q is an odd irreducible divisor of $1+P$ and we get the contradiction: $\deg(Q) < \deg(P) \leq \deg(Q)$.
ii): If d is even and if $d \geq 4$, then d is of the form $4r$ or $4r+2$. Thus, the odd polynomial $\sigma(Q^{2r})$ divides $\sigma^{**}(A) = A$, so we must have $P = \sigma(Q^{2r})$, which contradicts the fact: $\deg(P) \leq \deg(Q)$.
If $d = 2^\delta w - 1$ is odd (with w odd) and if $w \geq 3$, then $P = \sigma(Q^{w-1})$ and $\deg(P) > \deg(Q)$, which is impossible.
iii): From ii), $\sigma^{**}(Q^d) = (1+Q)^d$ so that $(1+Q)^d$ divides A. We may put: $1 + Q = x^{u_2}(x+1)^{v_2}P^{w_2}$, for some $u_2, v_2, w_2 \in \mathbb{N}$, $u_2, v_2 \geq 1$.
iv): $a, b \geq 3$ because $1+x$ divide $\sigma^{**}(x^a)$, x divides $\sigma^{**}((x+1)^b)$ and $x(x+1)$ divides both $\sigma^{**}(P^c)$ and $\sigma^{**}(Q^d)$.
From the proof of iii), x^{du_2} and $(x+1)^{dv_2}$ both divide A. Thus, $d \leq \min(a, b)$.
v) is immediate. $\square$

4.1 Case where $Q \in \mathcal{M}$

We get Proposition 4.2 from Lemma 4.5, by direct computations.

Proposition 4.2. *If A is b.u.p., where $P, Q \in \mathcal{M}$, then $A, \overline{A} \in \{C_8, \ldots, C_{13}\}$.*

Lemma 4.3. *The polynomials P and Q lie in $\mathcal{U} = \{M_1, M_2, M_3, M_4, M_5\}$.*

Proof. First, if $m \geq 1$ and if $\sigma(x^{2m})$ divides $\sigma^{**}(A)$, then $2m \leq 6$ and $\sigma(x^{2m}) \in \{M_1, M_4, M_2M_3\}$.
If $P, Q \notin \mathcal{U}$, then neither P nor Q divides $\sigma^{**}(x^a)\sigma^{**}((x+1)^b)$. So, $P \mid \sigma^{**}(Q^d)$, $P = \sigma(Q^{2m})$ with $m \geq 1$. It is impossible since $\deg(P) \leq \deg(Q)$.

If $P \in \mathcal{U}$ but $Q \notin \mathcal{U}$, then Q does not divide $\sigma^{**}(x^a)\sigma^{**}((x+1)^b)$. Hence, it must divide $\sigma(P^{2m})$, for some $m \geq 1$. Thus, $Q = \sigma(P^{2m})$. We get the contradiction: $x^{u_2}(x+1)^{v_2} = 1 + Q = 1 + \sigma(P^{2m})$ is divisible by P. $\square$

Lemma 4.4. *i) For $T \in \{P, Q\}$ and $m \geq 1$, $\sigma(T^{2m})$ does not divide $\sigma^{**}(A)$.*
ii) The exponents c and d lie in $\{2, 2^\gamma - 1 : \gamma \geq 1\}$.

Proof. i): For example, if $T = P$ and if $\sigma(T^{2m}) \mid \sigma^{**}(A) = A$, then we must have: $\sigma(T^{2m}) = Q$, which is impossible (see the proof of Lemma 4.3).
ii): If c is even and $c \neq 2$, then put $c = 4r$ or $c = 4r + 2$, with $r \geq 1$. $\sigma(P^{2r})$ divides $\sigma^{**}(A)$, which contradicts i).
If c is odd, then put $c = 2^\gamma u - 1$, with u odd and $\gamma \geq 1$. We also get a contradiction if $u \geq 3$, since $\sigma(P^{u-1})$ divides $\sigma^{**}(A)$.
The proof is similar for d. $\square$

Lemma 4.5. *The exponents a, b, c and d satisfy:*
$a \in \{4, 6, 8, 10, 12, 14\}$, $c, d \in \{1, 2, 3, 7\}$, if a is even
$b \in \{2^\beta v - 1 : \beta \in \{1, 2, 3\}, v \in \{1, 3, 5, 7\}\}$, if a is even and b odd
$a, b \in \{1, 3, 5, 7, 9, 11, 13\}$, $c, d \in \{1, 2, 3, 7\}$, if a and b are both odd.

Proof. We refer to Relations in (1) and in (3).
- If a is even, then $a \geq 4$, $a = 4r$ or $a = 4r + 2$ and $\sigma(x^{2r})$ divides $\sigma^{**}(A)$. So, $2r \leq 6$ and $c, d \leq a \leq 14$.
- If a is even and b odd, then $2^\beta - 1 \leq a \leq 14$ and $v \leq 7$.
- If a and b are both odd, then $u \geq 3$ or $v \geq 3$, $u, v \leq 7$. As in the proof of Lemma 3.4, if $u, v \geq 3$, then $\alpha = 1 = \beta$, then $a, b \leq 13$. If $u \geq 3$ and $v = 1$, then $b = 2^\beta - 1 \leq a \leq 13$ so that $b \leq 7$. If $u = 1$ and $v \geq 3$, then $\beta = 1$, then $a = 2^\alpha - 1 \leq 7$ and $b \leq 13$. $\square$

4.2 Case where $Q \notin \mathcal{M}$

We prove Proposition 4.6.

Proposition 4.6. *If A is b.u.p., where $P \in \mathcal{M}$ but $Q \notin \mathcal{M}$, then $A, \overline{A} \in \{D_1, D_2\}$.*

4.2.1 Useful facts

As in Lemma 3.1, one has: $a \geq 3$ or $b \geq 3$. Lemma 4.1 allows to write: $P = 1 + x^{u_1}(x+1)^{v_1}$ and $Q = 1 + x^{u_2}(x+1)^{v_2}P^{w_2}$, with $u_i, v_j, w_2 \geq 1$. We obtain Corollaries 4.20, 4.25 and 4.27. Only, the last of them gives b.u.p. polynomials, namely D_1, D_2, $\overline{D_1}$ and $\overline{D_2}$ (see Section 5).

For any $g \geq 1$, PQ is not of the form $\sigma(P^{2g})$, because P does not divide $\sigma(P^{2g})$. We shall see that it suffices to consider three cases (replace A by $\overline{A}$, if necessary): $PQ = \sigma(x^{2m})$, $Q = \sigma(x^{2m})$, $Q = \sigma(P^{2m})$, for some $m \geq 1$.

Lemma 4.7. *i) Let $n \geq 1$ be such that $\sigma(x^{2n})$ (resp. $\sigma((x+1)^{2n})$, $\sigma(P^{2n})$) divides $\sigma^{**}(A)$, then $\sigma(x^{2n}) \in \{P, Q, PQ\}$ (resp. $\sigma((x+1)^{2n}) \in \{P, Q, PQ\}$, $\sigma(P^{2n}) = Q$).*
ii) For any $n \geq 1$, $\sigma(Q^{2n})$ does not divide $\sigma^{**}(A)$.

Proof. Recall that we suppose: $\sigma^{**}(A) = A$.
i): $\sigma(x^{2n})$, $\sigma((x+1)^{2n})$ and $\sigma(P^{2n})$ are all odd and squarefree (Lemma 2.9). Hence, they belong to $\{P, Q, PQ\}$ whenever they divide $\sigma^{**}(A)$, with $\sigma(P^{2n}) \notin \{P, PQ\}$.
ii): If $\sigma(Q^{2n}) \mid \sigma^{**}(A)$, then $P^m = \sigma(Q^{2n})$, with $m = 1$, by Lemma 2.8-i). So, we get the contradiction: $\deg(Q) \geq \deg(P) = 2n \deg(Q) > \deg(Q)$. $\square$

Lemma 4.8 ([2], Lemma 4, page 726)**.**
The polynomial $1 + x(x+1)^{2^\nu - 1}$ is irreducible if and only if $\nu \in \{1, 2\}$.

Lemma 4.9. *If $\sigma(P^{2n})$ divides A for some $n \geq 1$, then $2n = 2^\gamma$, $2n - 1 \leq \min(a, b)$.*

Proof. Since $\sigma(P^{2n})$ is odd and square-free, Q must divide it. So $Q = \sigma(P^{2n})$. Put: $2n = 2^\gamma h$, with h odd.
We get: $1 + P + \cdots + P^{2n-1} = \dfrac{1 + \sigma(P^{2n})}{P} = \dfrac{1 + Q}{P} = x^{u_2}(x+1)^{v_2} P^{w_2 - 1}$.
Thus, $w_2 = 1$ and $(1 + P)^{2^\gamma - 1}(1 + P + \cdots + P^{h-1})^{2^\gamma} = 1 + P + \cdots + P^{2n-1} = x^{u_2}(x+1)^{v_2}$. Hence, $h = 1$, $2n - 1 \leq (2^\gamma - 1)u_1 = u_2 \leq a$ and $2n - 1 \leq (2^\gamma - 1)v_1 = v_2 \leq b$. $\square$

Lemma 4.10. *i) Let $P = M_4$ and $Q = 1 + x^5(x+1)^{2^\nu - 1} P^{2^\nu - 1}$, with $\nu \geq 1$. Then, Q is irreducible if and only if $\nu = 2$.*
ii) Let $P \in \{M_1, M_4\}$ and $Q = 1 + x(x+1)^{2^\nu - 1} P^{2^\nu}$, with $\nu \leq 10$. Then, Q is irreducible if and only if ($\nu = 2$, $P = M_1$) or ($\nu = 1$, $P = M_4$).
iii) Let $P \in \{M_1, M_4\}$ and $Q = 1 + P(1+P)^{2^\nu - 1}$. Then, Q is irreducible if and only if $P = M_1$ and $\nu \in \{1, 2\}$.

Proof. i): One has $Q = 1 + x^5(x+1)^{2^\nu - 1} P^{2^\nu - 1} = 1 + x^5(x^5+1)^{2^\nu - 1}$. The irreducibility of Q implies that $1 + x(x+1)^{2^\nu - 1}$ is irreducible. So, $\nu \in \{1, 2\}$ by Lemma 4.8.
If $\nu = 1$, then $Q = 1 + x^5 + x^{10} = (x^4 + x + 1)M_1 M_5$ is reducible.
If $\nu = 2$, then $Q = 1 + x^5 + x^{10} + x^{15} + x^{20}$ which is irreducible.
ii): by direct (Maple) computations.

iii): The polynomial $U = 1 + x(x+1)^{2^\nu - 1}$ must be irreducible, so $\nu \in \{1, 2\}$ by Lemma 4.8. Thus, $U \in \{M_1, M_4\}$.
If $P = U = M_1$, then $Q = 1 + x + x^4 = 1 + x(x+1)P$ is irreducible.
If $P = M_1$ and $U = M_4$, then $Q = 1 + x^3(x+1)^3 P$ is irreducible.
If $P = M_4$ and $U = M_1$, then $Q = 1+x(x+1)^3 P = (x^6+x^5+x^4+x^2+1)M_1$ is reducible.
If $P = U = M_4$, then $Q = 1 + x^3(x+1)^9 P = (x^{12} + x^9 + x^8 + x^7 + x^6 + x^4 + x^2 + x + 1)(1 + x + x^4)$ is reducible. $\square$

Lemma 4.11. *If $PQ = \sigma(x^{2n})$, then $(2n = 8, P = M_1, Q = 1 + x^3 + x^6)$ or $(2n = 24, P = M_4, Q = 1+x^5(x^5+1)^3)$. Moreover, $Q, \overline{Q} \notin \{\sigma(x^{2g}), \sigma(P^{2g}) : g \geq 1\}$ and $PQ \notin \{\sigma(x^{2g}), \sigma((x+1)^{2g}) : g \geq 1\}$.*

Proof. Since $PQ = \sigma(x^{2n})$, we get $P = P^*$ or $P = Q^*$. But, here, $\deg(P) < \deg(Q)$. So, $P = P^*$ and $Q = Q^*$. Since P is a Mersenne prime and $P = P^*$, one has $P = M_1$ or $P = M_4$. If $P = M_1$, then by Lemma 2.8-iv), $Q = 1+x^3(x+1)P = 1+x^3+x^6$. If $P = M_4$, then direct computations give $Q = 1 + x^5(x+1)^{2^\nu-1}P^{2^\nu-1}$. Since Q is irreducible, we get from Lemma 4.10-i), $\nu = 2$ and $Q = 1 + x^5(x^5 + 1)^3$. Thus, $Q \notin \{\sigma(x^6), \sigma((x+1)^6)\}$ (resp. $Q \notin \{\sigma(x^{20}), \sigma((x+1)^{20})\}$ if $P = M_1$ (resp. if $P = M_4$). We also remark that $\dfrac{\deg(Q)}{\deg(P)} \in \{3, 5\}$. So, $Q, \overline{Q} \notin \{\sigma(P^{2g}) : g \geq 1\}$. $\square$

Lemma 4.12. *If $Q = \sigma(x^{2n})$ with $n \geq 1$, then for some $\nu \geq 1$, $Q = 1 + x(x+1)^{2^\nu-1}{M_1}^{2^\nu}$ or $Q = 1 + x(x+1)^{2^\nu-1}{M_4}^{2^\nu}$. Moreover, $Q, \overline{Q} \notin \{\sigma(P^{2g}) : g \geq 1\}$ and $PQ \notin \{\sigma(x^{2g}), \sigma((x+1)^{2g}) : g \geq 1\}$.*

Proof. By direct computations, one has, for some $\nu \geq 1$: $2n = 2^\nu t$, $t \in \{3, 5\}$, $P = \sigma(x^{t-1})$ and $Q = 1 + x(x+1)^{2^\nu-1}P^{2^\nu}$. Hence, $P^{2^\nu} \| 1 + Q$.
If PQ is of the form $\sigma(x^{2g})$, then $P \| 1+Q$ or $P^3 \| 1+Q$ (Lemma 4.11), which is impossible.
Since $Q = \sigma(x^{2m})$, Lemma 4.14-i) implies that $Q \notin \{\sigma(P^{2m}), \sigma(\overline{P}^{\,2m})\}$. $\square$

Lemma 4.13. *If $Q = \sigma(P^{2n})$, then $2n \leq 4$, $P = M_1$, so that $Q \in \{1+x(x+1)M_1, 1+x^3(x+1)^3M_1\}$. Moreover, $Q, PQ \notin \{\sigma(x^{2g}), \sigma((x+1)^{2g}) : g \geq 1\}$.*

Proof. By direct computations, one has: $2n = 2^\nu, Q = 1+P(1+P)^{2^\nu-1}$, for some $\nu \geq 1$. Since Q is irreducible, we get $\nu \in \{1, 2\}$ and $P = M_1$. Again, by direct computations, $Q, PQ \notin \{\sigma(x^{2g}), \sigma((x+1)^{2g}) : g \geq 1\}$. $\square$

Lemma 4.14. *i) For any $m, n \in \mathbb{N}^*$, $\sigma(P^{2m}) \neq \sigma(x^{2n})$, $\sigma((x+1)^{2n})$.*
ii) If $\sigma(x^{2n}) = \sigma((x+1)^{2n})$, then $\sigma(x^{2n}) \notin \{Q, PQ\}$.

Proof. i): Put $2n-1 = 2^\alpha u - 1$ and $2m-1 = 2^\beta v - 1$, with $\alpha, \beta \geq 1$.
If $\sigma(P^{2m}) = \sigma(x^{2n})$, then $P(1+P+\cdots+P^{2m-1}) = x(1+x+\cdots+x^{2n-1})$.
Thus, $P(P+1)^{2^\beta-1}(1+P+\cdots+P^{v-1})^{2^\beta} = x(x+1)^{2^\alpha-1}(1+x+\cdots+x^{u-1})^{2^\alpha}$.
Hence, $u \geq 3$ and $2^\alpha = 1$, which is impossible.
ii): One has $2n = 2^h - 2$, for some $h \geq 1$ (Lemma 2.8-vii)). If $Q = \sigma(x^{2n})$, then by Lemma 4.12, $2^h - 2 = 2n = 2^\nu t$, with $t \in \{3, 5\}$. Therefore, $\nu = 1$, $t = 2^{h-1} - 1$, $h = 3 = t$, $2n = 6$ and $Q = M_2 M_3$ is reducible.
If $PQ = \sigma(x^{2n})$, then by Lemma 4.11, one has: ($2n = 8$, $P = M_1$ and $Q = 1+x^3+x^6$) or ($2n = 5 \cdot 2^\nu + 4$, $P = M_4$ and $Q = 1+x^5(x+1)^{2^\nu-1}P^{2^\nu-1}$).
Thus, $2^h - 2 = 2n = 5 \cdot 2^\nu + 4$, $\nu = 1$, $h = 4$ and $Q = 1 + x^5(x+1)P = (x^4+x+1)M_1 M_5$ is reducible. □

Without loss of generality, by Lemmas 4.11, 4.12 and 4.13, it suffices to consider the following three cases:

$$PQ = \sigma(x^{2m}),\ Q = \sigma(x^{2m}),\ Q = \sigma(P^{2m}), \text{for some } m \geq 1.$$

In each case, we distinguish: (a, b both even), (a even, b odd), (a, b both odd).
We shall compare a, b, c or d with all possible values of the exponents of x, $x+1$, of P or of Q, in $\sigma^{**}(A)$.

According to Corollary 2.3 and Lemma 4.1, we get Lemma 4.15 from Relations in (1) and in (4).

Lemma 4.15.
i) The polynomial P does not divide $\sigma^{**}(P^c)$, but it may divide $\sigma^{**}(Q^d)$.
ii) One has: $u_2 d \leq a$, $v_2 d \leq b$, $w_2 d \leq c$, so that $d \leq \min(a, b, c)$.

4.2.2 Case where $PQ = \sigma(x^{2m})$, for some $m \geq 1$

We get, from Lemma 4.11, $Q, \overline{Q} \notin \{\sigma(x^{2g}), \sigma(P^{2g}) : g \geq 1\}$, ($2m = 8, P = M_1$ and $Q = 1 + x^3 + x^6 = 1 + x^3(x+1)P$) or ($2m = 24, P = M_4$ and $Q = 1 + x^5(x^5+1)^3 = 1 + x^5(x+1)^3 P^3$).
We refer to Relations in (1) and in (4).

Lemma 4.16. *On has: $c = 2$ or $c = 2^\gamma - 1$, $c \leq \min(a, b)$ and $d = 1$.*

Proof. Since $Q \neq \sigma(P^{2g})$ for any g, $\sigma^{**}(P^c)$ must split, so $c = 2$ or $c = 2^\gamma - 1$. In this case, $\sigma^{**}(P^c) = (1+P)^c$, where P is a Mersenne prime. So, x^c and $(x+1)^c$ both divide $\sigma^{**}(A) = A$. Hence, $c \leq \min(a, b)$. Finally, $Q \| \sigma^{**}(A)$ because $Q, \overline{Q} \notin \{\sigma(x^{2g}), \sigma(P^{2g}) : g \geq 1\}$. Thus, $d = 1$. □

Lemma 4.17. *At least, one of a and b is even.*

Proof. If a and b are both odd, then $PQ = \sigma(x^{u-1})$, $\sigma((x+1)^{v-1}) \in \{1, P\}$, $d = 2^\alpha$, $c = w_2 d + 2^\alpha + \varepsilon_2 2^\beta$. It follows that c is even and $c \geq 4$, which contradicts Lemma 4.16. $\square$

Lemma 4.18. *If a and b are both even, then $a = 16$, $b \in \{4, 6\}$, $c \leq 3$, $P = M_1$ and $Q = 1 + x^3(x^3 + 1)$.*

Proof. Lemma 4.1-iv) implies that $a, b \geq 4$. Moreover, $PQ \in \{\sigma(x^{2r}), \sigma(x^{u-1})\}$. If $PQ = \sigma(x^{2r})$, then $P = \sigma((x+1)^{2s})$, $u = v = 1$ because $\gcd(\sigma(x^{2r}), \sigma(x^{u-1})) = 1 = \gcd(\sigma((x+1)^{2s}), \sigma((x+1)^{v-1}))$. Therefore, $2r = 8$, $a \neq 4r + 2$, $2s = 2$, $a = 16$, $b \in \{4, 6\}$. Furthermore, $c \leq b \leq 6$, so that $c \in \{1, 2, 3\}$.
If $PQ = \sigma(x^{u-1})$, then $\sigma(x^{2r}) = P$ (by Lemma 4.7), which is impossible since $\gcd(\sigma(x^{2r}), \sigma(x^{u-1})) = 1$. $\square$

Lemma 4.19. *If a is even and b odd, then $a = 16$, $b \in \{1, 3, 7\}$, $c = 2$, $P = M_1$ and $Q = 1 + x^3(x^3 + 1)$.*

Proof. As above, a even implies that $a = 4r = 16$ and $P = M_1$. One has: $\sigma((x+1)^{v-1}) \in \{1, P\}$. So, $v \in \{1, 3\}$, $c = 1 + w_2 d + \varepsilon_2\, 2^\beta$, where $w_2 = 1 = d$. Thus, $c = 2$, $v = 1$, $2^\beta - 1 + 3 + 2 \leq a = 16$, $\beta \leq 3$ and $b \in \{1, 3, 7\}$. $\square$

Corollary 4.20. *If A is b.u.p., with PQ of the form $\sigma(x^{2m})$, then $P = M_1$, $Q = 1 + x^3(x^3 + 1)$, $a, b \in \{1, 3, 4, 6, 7, 16\}$, $c \leq 3$ and $d = 1$.*

4.2.3 Case where $Q = \sigma(x^{2m})$, for some $m \geq 1$

One has (Lemma 4.12): $Q, \overline{Q} \notin \{\sigma(P^{2g}) : g \geq 1\}$, $PQ \notin \{\sigma(x^{2g}), \sigma((x+1)^{2g}) : g \geq 1\}$, $2m \geq 10$, $P \in \{M_1, M_4\}$ and $Q = 1 + x(x+1)^{2^\nu - 1} P^{2^\nu}$, for some $\nu \in \mathbb{N}^*$. So, $u_1 = u_2 = 1$, $v_1 \in \{1, 3\}$, $v_2 = 2^\nu - 1$ and $w_2 = 2^\nu$. Moreover, $Q \neq \sigma((x+1)^{2m})$ (Lemma 4.14).
We consider Relations in (1) and in (4).

Lemma 4.21. *One has: ($c = 2$ or $c = 2^\gamma - 1$) and $d \leq 3$.*

Proof. If $\sigma^{**}(P^c)$ does not split, then Q is the unique odd irreducible divisor of $\sigma^{**}(P^c)$. It contradicts the fact that Q is not of the form $\sigma(P^{2g})$. So, $\sigma^{**}(P^c)$ splits and ($c = 2$ or $c = 2^\gamma - 1$). The exponent of Q in $\sigma^{**}(A)$ lies in $\{1, 2, 2^\alpha, 2^\beta, 1 + 2^\alpha, 1 + 2^\beta, 2^\alpha + 2^\beta\}$. So, by Lemma 4.1-ii), $d \leq 3$. $\square$

Lemma 4.22. *At least, one of a and b is even.*

Proof. If a and b are both odd, then $Q = \sigma(x^{u-1})$, $Q \neq \sigma((x+1)^{v-1})$ (by Lemma 4.14-ii)) and $\sigma((x+1)^{v-1}) \in \{1, P\}$. Thus, $v \in \{1, 3, 5\}$, $2^\alpha = d \leq 3$, $\alpha = 1$, $d = 2$, $c = 2 \cdot 2^\nu + \varepsilon_2 2^\beta$. So, c is even and $c \geq 4$. It contradicts Lemma 4.21. □

Lemma 4.23. *If a and b are even, then $\nu \leq 2$, $20 \leq a \leq 26$, $b \leq 10$, $d = 1$, $c \in \{1, 2, 3, 7\}$, and $(P, Q) \in \{(M_1, 1 + x(x+1)^3 P^4), (M_4, 1 + x(x+1)P^2)\}$.*

Proof. One has: $Q \in \{\sigma(x^{2r}), \sigma(x^{u-1})\}$.
- If $Q = \sigma(x^{2r})$, then $Q \neq \sigma((x+1)^{2s})$ (by Lemma 4.14-ii)), Q does not divide $\sigma(x^{u-1})$ since $\gcd(\sigma(x^{2r}), \sigma(x^{u-1})) = 1$. So, $Q \| \sigma^{**}(A)$. Therefore, $d = 1$, $P = \sigma((x+1)^{2s})$, $\sigma(x^{u-1}) \in \{1, P\}$, $u \in \{1, 3, 5\}$, $v = 1$, $2s \leq 4$, $b \leq 10$, $c = 2^\nu + \varepsilon_1 2^\alpha + 1 \geq 3$. Since $2^\alpha + c \leq b \leq 10$, we get: $c \in \{1, 2, 3, 7\}$, $\alpha \leq 2$, $\nu \leq 2$.
Here, $Q = 1 + x(x+1)^{2^\nu - 1} P^{2^\nu}$, with $P \in \{M_1, M_4\}$ and $\nu \leq 2$. By Lemma 4.10-ii), one has: ($P = M_1$, $\nu = 2$ and $2r = 12$) or ($P = M_4$, $\nu = 1$ and $2r = 10$). So, $20 \leq a \leq 26$.
- If $Q = \sigma(x^{u-1})$, then $2^\alpha = d \leq 3$ and $P = \sigma(x^{2r}) = \sigma((x+1)^{2s})$. Thus, $d = 2$, $2r = 2s = 2$, $a, b \in \{4, 6\}$, $c = 2 + w_2 d = 2 + 2w_2 \geq 4$. It contradicts Lemma 4.21. □

Lemma 4.24. *The case where a is even and b odd does not happen.*

Proof. If a is even and b odd, then $Q \in \{\sigma(x^{2r}), \sigma(x^{u-1})\}$.
- If $Q = \sigma(x^{2r})$, then $d = 1$, $\sigma(x^{u-1}), \sigma((x+1)^{v-1}) \in \{1, P\}$, $u, v \in \{1, 3, 5\}$, $w_2 d = 2^\nu$, $c = 2^\nu + \varepsilon_1 2^\alpha + \varepsilon_2 2^\beta$ is even.
Therefore, $c = 2$, $\nu = 1$, $\varepsilon_1 = \varepsilon_2 = 0$ and $u = v = 1$.
By Lemma 4.10-ii), since $\nu = 1$, one has: $P = M_4$ and thus $v_1 = 3, v_2 = 1, w_2 = 2$, $2r = \deg(Q) = 2^\nu(1 + \deg(P)) = 2^\nu \cdot 5 = 10$. We get the contradiction: $a \in \{20, 22\}$ and $a = 2^\beta - 1 + 2u_1 + u_2 = 2^\beta - 1 + 2 + 1 = 2^\beta + 2$.
- If $Q = \sigma(x^{u-1})$, then $a > u - 1 = 2m \geq 10$, $P = \sigma(x^{2r})$, $2^\alpha = d \leq 3$. Hence, $d = 2$, $2r \leq 4$, $a \in \{4, 6, 8, 10\}$. We get the contradiction: $a > 10 \geq a$. □

Corollary 4.25. *If A is b.u.p., with Q of the form $\sigma(x^{2m})$, then $(P, Q) = (M_1, 1 + x(x+1)^3 {M_1}^4)$ or $(P, Q) = (M_4, 1 + x(x+1){M_4}^2)$, $a, b \in \{4, 6, 8, 10, 20, 22, 24, 26\}$, $c \in \{1, 2, 3, 7\}$, $d = 1$.*

4.2.4 Case where $Q = \sigma(P^{2m})$, for some $m \geq 1$

Lemma 4.13 implies that $Q, PQ \notin \{\sigma(x^{2g}), \sigma((x+1)^{2g}) : g \geq 1\}$. $P = M_1$ and ($Q = \sigma(P^2) = 1 + x(x+1)P$ or $Q = \sigma(P^4) = 1 + x^3(x+1)^3 P$). Thus, $u_1 = v_1 = 1$, $u_2 = v_2 \in \{1, 3\}, w_2 = 1$.

Lemma 4.26. *The integer $a+b$ is odd, $a, b \leq 11$, $c \leq 8$ and $d \leq 3$.*

Proof. We refer to Relations in (1) and in (4). Lemma 4.7 is also useful.
If c is even, then $2m = 2t \geq 2$, $\sigma(P^{2t}) = Q$. So, $w = 1, d = 1$. If c is odd, then $Q = \sigma(P^{w-1}), w \in \{3, 5\}, d = 2^{\gamma}$.
- If a and b are even, then $a, b \geq 4$ (by Lemma 4.1-iv)), $P = \sigma(x^{2r}) = \sigma((x+1)^{2s})$. Hence, $u = v = 1$, $2r = 2s = 2$, $a, b \leq 6$ and $c = 2 + d$ (by considering the exponents of P). We get a contradiction on the value of c.
- If a and b are odd, then $\sigma(x^{u-1}), \sigma((x+1)^{v-1}) \in \{1, P\}$, so that $u, v \leq 3$. Moreover, if c is even, then $\sigma(P^{2t}) = Q$, $w = 1$, $d = 1$ and $c \in \{1, 1+2^{\alpha}, 1+2^{\beta}, 1+2^{\alpha}+2^{\beta}\}$. It contradicts the parity of c. If c is odd, then $Q = \sigma(P^{w-1})$, $w \in \{3, 5\}$, $d = 2^{\gamma}$, so that $d = 2$ and $c \in \{2, 2+2^{\alpha}, 2+2^{\beta}, 2+2^{\alpha}+2^{\beta}\}$. We also get a contradiction on the value of c.
- If a is even and b odd, then $a \geq 4$ (Lemma 4.1), $\sigma(x^{2r}) = P = M_1$, $u = 1$, $2r = 2$, $a \leq 6$. Moreover, $\sigma((x+1)^{v-1}) \in \{1, P\}$, so $v \leq 3$. We get $\beta \leq 2$, $b \leq 11$, $d \leq 3$ and $c \leq 8$ because $2^{\beta} - 1 \leq a \leq 6$, $d \leq a \leq 6$ and $c \in \{1+d, 1+2^{\beta}+d\}$.
The proof is similar if a is odd and b even. $\square$

Corollary 4.27. *If A is b.u.p., with Q of the form $\sigma(P^{2m})$, then $P = M_1$, $Q \in \{1 + x(x+1)P, 1 + x^3(x+1)^3P\}$, $a+b$ is odd, $a, b \leq 11$, $c \leq 8, d \leq 3$.*

5 Maple Computations

The function σ^{**} is defined as Sigm2star, for the Maple code.

```
> Sigm2star1:=proc(S,a) if a=0 then 1;else if a mod 2 = 0
then n:=a/2:sig1:=sum(S^l,l=0..n):sig2:=sum(S^l,l=0..n-1):
Factor((1+S)*sig1*sig2) mod 2:
else Factor(sum(S^l,l=0..a)) mod 2:fi:fi:end:
> Sigm2star:=proc(S) P:=1:L:=Factors(S) mod 2:k:=nops(L[2]):
for j to k do S1:=L[2][j][1]:h1:=L[2][j][2]:
P:=P*Sigm2star1(S1,h1):od:P:end:
```

We search all $S = x^a(x+1)^bP^c$ or $S = x^a(x+1)^bP^cQ^d$ such that $\sigma^{**}(S) = S$.

5.1 Case where $\omega(A) = 3$

We have proved that $P \in \{M_1, M_4, M_5\}$. By means of Lemma 3.4. We obtain $C_1, \ldots, C_7$.

5.2 Case where $\omega(A) = 4$ with $P, Q \in \mathcal{M}$

We have shown that $P, Q \in \{M_1, M_2, M_3, M_4, M_5\}$. From Lemma 4.5, we obtain $C_8, \ldots, C_{13}$.

5.3 Case where $\omega(A) = 4$ with $P \in \mathcal{M}, Q \notin \mathcal{M}$

We apply Corollaries 4.20, 4.25 and 4.27.
1) If Q or PQ is of the form $\sigma(x^{2m})$, then we obtain no b.u.p. polynomials.
2) If Q is of the form $\sigma(P^{2m})$, then we get D_1, D_2, $\overline{D}_1$ and $\overline{D}_2$.

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