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ON WENDT'S DETERMINANT

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Abstract. Wendt's determinant of order m is the circulant determinant W_m whose (i,j)-th entry is the binomial coefficient $\binom{m}{|i-j|}$, for $1 \le i, j \le m$. We give a formula for W_m, when m is even not divisible by 6, in terms of the discriminant of a polynomial T_{m+1}, with rational coefficients, associated to $(X+1)^{m+1} - X^{m+1} - 1$. In particular, when $m = p-1$ where p is a prime $\equiv -1$ $(mod\ 6)$, this yields a factorization of W_{p-1} involving a Fermat quotient, a power of p and the 6-th power of an integer.

Introduction

E. Wendt ([12]) introduced the $m \times m$ circulant determinant W_m with first row the binomial coefficients $\binom{m}{0}, \binom{m}{1}, \dots, \binom{m}{m-1}$, i.e.

$$W_m = \begin{vmatrix} 1 & \binom{m}{1} & \binom{m}{2} & \dots & \binom{m}{m-1} \\ \binom{m}{m-1} & 1 & \binom{m}{1} & \dots & \binom{m}{m-2} \\ \vdots & \vdots & \vdots & & \vdots \\ \binom{m}{1} & \binom{m}{2} & \binom{m}{3} & \dots & 1 \end{vmatrix},$$

which is the resultant of the polynomials $X^m - 1$ and $(X+1)^m - 1$, in connection with Fermat's last theorem ([10]). E. Lehmer ([9]) proved that $W_m = 0$ if and only if $m \equiv 0$ $(mod\ 6)$, and that if p is an odd prime number, then W_{p-1} is divisible by $p^{p-2}q_p(2)$, where $q_p(2) = \frac{2^{p-1}-1}{p}$ is a Fermat quotient. L. Carlitz ([2]) determined W_{p-1} modulo p^{p-1}, which he then used to find high powers of p dividing W_{p-1} in an application in the same connection ([3]). Factorizations of the integers W_m for $m \le 50$ were given in ([7]). The size of W_m was investigated in ([1]). Granville and Fee ([5]) determined the prime factors of W_m for all even $m \le 200$ and consequently improved on a classical result about Fermat's equation. This was further improved in ([6]), where similar computations were carried up to $m \le 500$.

In this article, we show that for all positive even integers m not divisible by 6,

$$W_m = -9^{h_m}(2^m - 1)^3(m+1)^{m-4|h_m|}D_m^6,$$

where D_m is the discriminant of a polynomial with rational coefficients whose roots are given by a rational function of those of $(X+1)^{m+1} - X^{m+1} - 1$, and $h_m = 2$ or -1 according as $m \equiv 2$ or 4 $(mod\ 6)$ respectively. In particular, if p is a prime $\equiv -1$ $(mod\ 6)$ then D_{p-1} is a rational integer and we have the factorization

$$W_{p-1} = -\frac{1}{9}q_p(2)^3 p^{p-2} D_{p-1}^6.$$

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1. Preliminary results

For any positive integer m, let ζ_m be a primitive m-th root of unity in $\mathbb{C}$. By a well-known expression for circulant determinants ([12]),

$$W_m = \prod_{j=0}^{m-1} \left(\sum_{k=0}^{m-1} \binom{m}{k} \zeta_m^{jk} \right) = \prod_{j=0}^{m-1} \left((1+\zeta_m^j)^m - 1 \right). \tag{1}$$

Denote by n an odd integer ≥ 3 and consider the polynomial

$$P_n(X) = (X+1)^n - X^n - 1. \tag{2}$$

Its relation to Wendt's determinant is the following

Proposition 1. *For any odd integer $n \geq 3$, the discriminant of P_n is*

$$D(P_n) = (-1)^{\frac{n-1}{2}} n^{n-2} W_{n-1}.$$

Proof. Since P_n has degree $n-1$ and leading coefficient n, we have ([4] or [11]) $D(P_n) = (-1)^{\frac{(n-1)(n-2)}{2}} n^{-1} R(P_n, P_n')$, where $R(P_n, P_n')$ is the resultant of P_n and its derivative P_n'. We also have $R(P_n, P_n') = (n(n-1))^{n-1} \prod_{k=1}^{n-2} P_n(y_k)$, where $y_k = \frac{1}{\zeta_{n-1}^k - 1}$ $(1 \leq k \leq n-2)$ are the roots of $P_n'(X) = n((X+1)^{n-1} - X^{n-1})$ in $\mathbb{C}$. Every $P_n(y_k) = \frac{1-(\zeta_{n-1}^k - 1)^{n-1}}{(\zeta_{n-1}^k - 1)^{n-1}}$, for $1 \leq k \leq n-2$. The product $\prod_{k=1}^{n-2}(1-\zeta_{n-1}^k)$ is the value at 1 of $(X^{n-1}-1)/(X-1)$, which is $n-1$. Moreover, since n is odd,

$$\prod_{k=1}^{n-2} \left(1 - (\zeta_{n-1}^k - 1)^{n-1}\right) = \prod_{k=0}^{n-2} \left(\left(1 + \zeta_{n-1}^{k+\frac{n-1}{2}}\right)^{n-1} - 1 \right) = W_{n-1},$$

by (1). Hence $\prod_{k=1}^{n-2} P_n(y_k) = \frac{W_{n-1}}{(n-1)^{n-1}}$ and the result follows by substitution.

Now the polynomial P_n can be written ([8])

$$P_n(X) = X(X+1)(X^2+X+1)^{e_n} F_n(X), \tag{3}$$

where F_n lies in $\mathbb{Z}[X]$, is prime to $X(X+1)(X^2+X+1)$, has degree $d_n = n-3-2e_n$ and leading coefficient n, with $e_n = 0,\ 1$ or 2 according as $n \equiv 0,\ 2$ or 1 $(mod\ 3)$ respectively. It follows from (2) and (3) that $F_n(-X-1) = F_n(X)$ and $F_n(1/X) = F_n(X)/X^{d_n}$. Hence the set of roots z of F_n in $\mathbb{C}$ is partitioned into $r_n = d_n/6$ orbits of 6 elements each, namely

$$Orb(z) = \{z,\ \frac{1}{z},\ -z-1,\ -\frac{1}{z+1},\ -\frac{z+1}{z},\ -\frac{z}{z+1}\}. \tag{4}$$

Let $z_1, \ldots, z_{r_n}$ be representatives of the different orbits of roots of F_n. For every $1 \leq j \leq r_n$, let g_j be the monic polynomial whose roots are the elements of $Orb(z_j)$. A straightforward computation gives

$$g_j(X) = X^6 + 3X^5 + t_j X^4 + (2t_j - 5)X^3 + t_j X^2 + 3X + 1 \quad (1 \leq j \leq r_n) \tag{5}$$

where

$$t_j = 6 - J(z_j), \qquad J(X) = \frac{(X^2+X+1)^3}{X^2(X+1)^2} \tag{6}$$

and

$$F_n = n \prod_{j=1}^{r_n} g_j. \tag{7}$$

Moreover

(8) $$g_j(X) = X^2(X+1)^2\,(J(X) - J(z_j)) \quad (1 \le j \le r_n).$$

We now introduce the polynomial

(9) $$T_n(X) = \prod_{j=1}^{r_n}(X - t_j)$$

which lies in $\mathbb{Q}[X]$, since the automorphisms of the splitting field of F_n over $\mathbb{Q}$ permute the roots of T_n and thus leave its coefficients fixed. Substituting (8) into (7) yields

(10) $$F_n(X) = (-1)^{r_n} n X^{2r_n}(X+1)^{2r_n} T_n(6 - J(X)).$$

This relation, linking T_n to F_n and thus to P_n, facilitates computations with T_n.

2. Discriminants calculations

The resultant of two non-zero polynomials $f, g \in \mathbb{C}[X]$ is denoted by $R(f,g)$ and the discriminant of f by $D(f)$. The classic formula ([4]) $D(fg) = D(f)D(g)R(f,g)^2$ yields by induction

Lemma 1. *If $f_1, \ldots, f_m$ are non-constant polynomials in $\mathbb{C}[X]$, then*

$$D\left(\prod_{i=1}^{m} f_i\right) = \prod_{i=1}^{m} D(f_i). \prod_{1 \le i < j \le m} R(f_i, f_j)^2.$$

Using this, the relation (3) allows, when $e_n < 2$, to express $D(F_n)$ in terms of $D(P_n)$. Indeed,

Lemma 2. *For a positive odd integer $n \not\equiv 1$ (mod 6),*

$$D(F_n) = \frac{(-1)^{e_n} D(P_n)}{3^{e_n} n^{4(e_n+1)}}.$$

Proof. Assume first $n \equiv -1$ (*mod* 6), so that $e_n = 1$ and

$$P_n(X) = X(X+1)(X^2+X+1)F_n(X).$$

From Lemma 1,

$$D(P_n) = -3(F_n(0)F_n(-1)F_n(\zeta_3)F_n(\zeta_3^2))^2 D(F_n).$$

Now, for all odd n, $F_n(0) = F_n(-1) = n$, since these are the values of $P_n(X)/X$ at 0 and $-P_n(X)/(X+1)$ at -1 respectively. On the other hand, setting $P_n(X) = (X^2+X+1)Q_n(X)$, with $Q_n \in \mathbb{Z}[X]$, we have

$$F_n(\zeta_3) = \frac{Q_n(\zeta_3)}{\zeta_3(\zeta_3+1)} = -\frac{P_n'(\zeta_3)}{2\zeta_3+1} = -\frac{n\left((\zeta_3+1)^{n-1} - \zeta_3^{n-1}\right)}{2\zeta_3+1} = n.$$

Also, $F_n(\zeta_3^2)$, being the complex conjugate of $F_n(\zeta_3)$, is equal to n too. Hence $D(P_n) = -3n^8 D(F_n)$. Similarly, in the simpler case where $n \equiv 3$ (*mod* 6), we have $P_n(X) = X(X+1)F_n(X)$ so that $D(P_n) = (F_n(0)F_n(-1))^2 D(F_n) = n^4 D(F_n)$.

We now relate the discriminants of F_n, T_n and the g_j's.

Lemma 3. *For any odd integer $n \ge 3$,*

$$D(F_n) = n^{2(d_n-1)}. \prod_{j=1}^{r_n} D(g_j).D(T_n)^6.$$

Proof. By (7) and Lemma 1, $D(F_n) = n^{2(d_n-1)}.\prod_{j=1}^{r_n} D(g_j).\prod_{1\le i<j\le r_n} R(g_i,g_j)^2$. By (8), for $1 \le i,j \le r_n$, $R(g_i,g_j) = \prod_z g_j(z) = (J(z_i) - J(z_j))^6 \left(\prod_z z(z+1)\right)^2$, where the products are for z ranging in $Orb(z_i)$, in which case $J(z) = J(z_i)$ by (5) and (6). Moreover, $\prod_z z = g_j(0) = 1$ and $\prod_z(z+1) = g_j(-1) = 1$. Hence $R(g_j,g_i) = R(g_i,g_j) = (J(z_i) - J(z_j))^6$. On the other hand, $D(T_n) = (-1)^{r_n(r_n-1)/2}\prod_{i\ne j}(t_i - t_j) = \pm\prod_{i\ne j}(J(z_j) - J(z_i))$, where the products are for all $i,j \in \{1,\dots,r_n\}$ with $i \ne j$. Hence $\prod_{1\le i<j\le r_n} R(g_i,g_j)^2 = \prod_{i\ne j} R(g_i,g_j) = \prod_{i\ne j}(J(z_i) - J(z_j))^6 = D(T_n)^6$ and the result follows.

Next, we compute the dicriminants of the g_j's.

Lemma 4. *For any odd integer $n \ge 3$ and $1 \le j \le r_n$,*

$$D(g_j) = -(4t_j+3)^3(t_j-6)^4.$$

Proof. Let $Y = X + 1/X$. Then $g_j(X) = X^3h_j(Y)$, where $h_j(Y) = Y^3 + 3Y^2 + (t_j-3)Y + 2t_j - 11$; and $g_j'(X) = 3g_j(X)/X + (X^3 - X)h_j'(Y)$. Hence

$$D(g_j) = -\prod_z g_j'(z) = -\left(\prod_z z\right)\left(\prod_z (z+1)\right)\left(\prod_z (z-1)\right)\prod_z h_j'(z+\frac{1}{z}),$$

where the products are for $z \in Orb(z_j)$. From the proof of Lemma 3, $\prod_z z = \prod_z(z+1) = 1$. Also $\prod_z(z-1) = g_j(1) = 4t_j + 3$. Moreover, $y = z + 1/z$ ranges through the roots of h_j, each repeated twice, as z ranges through $Orb(z_j)$, so that $\prod_z h_j'(z+1/z) = \left(\prod_y h_j'(y)\right)^2 = D(h_j)^2$. Thus $D(g_j) = -(4t_j+3)D(h_j)^2$. Now, setting $U = Y + 1$, we have $h_j(Y) = f_j(U) = U^3 + (t_j-6)U + t_j - 6$. By a well-known formula for the discriminant of a cubic polynomial ([11]), we get $D(h_j) = D(f_j) = -(4t_j+3)(t_j-6)^2$. Hence the result.

The product, appearing in Lemma 3, of the discriminants of the g_j's is given by

Lemma 5. *For any odd integer $n \ge 3$,*

$$\prod_{j=1}^{r_n} D(g_j) = (-1)^{r_n}3^{4-7e_n}(2^{n-1}-1)^3 n^{4e_n-7}\left(\frac{n-1}{2n}\right)^{2e_n(e_n-1)}.$$

Proof. By Lemma 4,

$$\prod_{j=1}^{r_n} D(g_j) = (-1)^{r_n}\left(\prod_{j=1}^{r_n}(4t_j+3)\right)^3\left(\prod_{j=1}^{r_n}(t_j-6)\right)^4. \tag{11}$$

Now $\prod_{j=1}^{r_n}(4t_j+3) = (-4)^{r_n}T_n(-3/4)$. Moreover, substituting $X = 1$ into (10) and (3), we get $(-4)^{r_n}nT_n(-3/4) = F_n(1) = P_n(1)/(2.3^{e_n})$. Hence

$$\prod_{j=1}^{r_n}(4t_j+3) = \frac{F_n(1)}{n} = \frac{2^{n-1}-1}{3^{e_n}n}. \tag{12}$$

Similarly, $\prod_{j=1}^{r_n}(t_j-6) = (-1)^{r_n}T_n(6)$, and substituting $X = \zeta_3$ into (10) yields $(-1)^{r_n}nT_n(6) = F_n(\zeta_3)$. Let $Q_n(X) = X(X+1)F_n(X)$; then $F_n(\zeta_3) = -Q_n(\zeta_3)$ and, by (3), $P_n(X) = (X^2+X+1)^{e_n}Q_n(X)$. Taking e_n-th derivatives in the latter relation and making $X = \zeta_3$, we get $Q_n(\zeta_3) = P_n^{(e_n)}(\zeta_3)/(e_n!(2\zeta_3+1)^{e_n})$ (here

$2\zeta_3 + 1$ is the value of the factor $X - \zeta_3^2$ in $X^2 + X + 1$, and the equality follows from Taylor's formula). Hence

$$\prod_{j=1}^{r_n}(t_j - 6) = \frac{F_n(\zeta_3)}{n} = -\frac{P_n^{(e_n)}(\zeta_3)}{e_n! n(2\zeta_3 + 1)^{e_n}}.$$

Simple computations show that $-P_n^{(e_n)}(\zeta_3)/(2\zeta_3 + 1)^{e_n} = 3$ or n or $n(n-1)/3$ according as $n \equiv 0$ or 2 or 1 (*mod* 3) respectively. Therefore $\prod_{j=1}^{r_n}(t_j - 6) = 3/n$ or 1 or $(n-1)/6$ respectively. One formula representing all three cases is

$$\prod_{j=1}^{r_n}(t_j - 6) = \left(\frac{n}{3}\right)^{e_n - 1}\left(\frac{n-1}{2n}\right)^{\frac{e_n(e_n-1)}{2}}. \tag{13}$$

Substituting (12) and (13) into (11) yields the desired result.

3. Conclusion

We can now draw the formula relating Wendt's determinant W_{n-1} to the discriminant of the polynomial T_n, namely

Proposition 2. *For any odd positive integer $n \not\equiv 1$ (mod 6),*

$$W_{n-1} = -9^{2-3e_n}\left(2^{n-1} - 1\right)^3 n^{n+4e_n-9} D(T_n)^6,$$

where $e_n = 0$ or 1 according as $n \equiv 3$ or -1 (mod 6) respectively, and T_n is defined by (9).

Proof. By Lemmas 3 and 5, since $d_n = n - 3 - 2e_n$ and $e_n = 0$ or 1, we have $D(F_n) = (-1)^{r_n} 3^{4-7e_n}(2^{n-1} - 1)^3 n^{2n-15} D(T_n)^6$. On the other hand, Proposition 1 and Lemma 2 imply $D(F_n) = (-1)^{e_n + (n-1)/2} 3^{-e_n} n^{n-4e_n-6} W_{n-1}$. Equating the two expressions (and noting that $r_n + e_n + (n-1)/2 = 2(n + e_n)/3 - 1$ is odd) yields the desired result.

Remark. In Proposition 2, let $m = n - 1$ and $h_m = 2 - 3e_n$, so that m is an even positive integer $\not\equiv 0$ (*mod* 6) and $h_m = 2$ or -1 according as $m \equiv 2$ or 4 (*mod* 6) respectively. Noting that $2 - e_n$ coincides with $|h_m|$ and writing D_m for $D(T_{m+1})$, we obtain the formula for W_m stated in the Introduction.

Assume now that $n = p$ is a prime number $\equiv -1$ (*mod* 6). Then the leading coefficient p of P_p divides all its coefficients $\binom{p}{k}$, for $1 \le k \le p - 1$, so that, by (3), $F_p = pE_p$ where E_p is a monic polynomial in $\mathbb{Z}[X]$. Thus the roots of F_p are algebraic integers. Since, by (5), t_j is a sum of products of roots of F_p, then t_j is also an algebraic integer, for $1 \le j \le r_p$. Hence T_p has rational integer coefficients and $D(T_p)$ lies in $\mathbb{Z}$. Therefore Proposition 2 (where now $e_p = 1$) implies

Corollary. *If p is a prime number $\equiv -1$ (mod 6), then*

$$W_{p-1} = -\frac{1}{9} q_p(2)^3 p^{p-2} D(T_p)^6,$$

where the discriminant $D(T_p)$ is a rational integer and $q_p(2) = \frac{2^{p-1}-1}{p}$.

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