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On the coefficients of the 2^n-th transformation polynomial for $j(\omega)$

by

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In memory of Professor Wacław Sierpiński

Let $j(\omega)$ be the modular function of level 1. It is well known that there exists to every integer $m \geqslant 2$ an irreducible polynomial

$$F_m(u, v) = F_m(v, u)$$

with rational integral coefficients such that

$$F_m\big(j(m\omega), j(\omega)\big) = 0 \quad \text{identically in } \omega.$$

As m increases, the coefficients of $F_m(u, v)$ soon become extremely large. But how large they do in fact become does not seem to have been studied in the literature.

We shall consider here only the case when

$$m = 2^n$$

is a power of 2. Let the abbreviation $F_{(n)}(u, v)$ stand for $F_{2^n}(u, v)$, and let $L(F_{(n)})$ be the sum of the absolute values of the coefficients of $F_{(n)}(u, v)$. It will then be proved that

$$L(F_{(n)}) \leqslant 2^{(36n+57)2^n} \quad (n = 1, 2, 3, \ldots).$$

I hope to establish in a later paper an analogous estimate for the general polynomial $F_m(u, v)$.

1. The following notation will be used.

If $P(u, v, \ldots)$ is a polynomial with complex coefficients in the indeterminates $u, v, \ldots$, then $\partial_u(P)$, $\partial_v(P)$, ... denote the exact degrees of P in $u, v, \ldots$, respectively, and we put

$$\Delta(P) = \partial_u(P) + \partial_v(P) + \ldots$$

Further $L(P)$, the *length* of P, is defined as the sum of the absolute values of the coefficients of P. This length evidently has the properties

(1) $$L(P+Q) \leqslant L(P) + L(Q) \quad \text{and} \quad L(PQ) \leqslant L(P)L(Q),$$

and it can also be proved (Mahler, [1]) that, if P allows the factorisation

$$P = P_1 P_2 \dots P_r,$$

then

(2) $$L(P_1)L(P_2)\dots L(P_r) \leqslant 2^{\Delta(P)} L(P).$$

Next let $\omega = \xi + i\eta$ be a complex variable in the upper halfplane

$$H:\ \eta > 0,$$

and let as usual q denote the expression $q = e^{\pi i \omega}$, so that $0 < |q| < 1$. We shall be concerned with the basic modular function

(3) $$j(\omega) = \left\{1 + 240 \sum_{h=1}^{\infty} h^3 \frac{q^{2h}}{1-q^{2h}}\right\}^3 \left\{q^2 \prod_{h=1}^{\infty} (1-q^{2h})^{24}\right\}^{-1}$$

of level 1, and also with the modular function

(4) $$k(\omega) = 4q^{1/2} \prod_{h=1}^{\infty} \left\{\frac{1+q^{2h}}{1+q^{2h-1}}\right\}^4$$

of Legendre and Jacobi of level 4. These two functions are connected by the identity

(5) $$j(\omega) = 2^8 \frac{\{k(\omega)^4 - k(\omega)^2 + 1\}^3}{k(\omega)^4\{1-k(\omega)^2\}^2}.$$

We shall further make use of Gauss's formula

(6) $$k(\omega/2) = \frac{2\sqrt{k(\omega)}}{1+k(\omega)}.$$

2. It is proved in the theory of modular functions that, for every positive integer n, there exists an irreducible polynomial

(7) $$F_{(n)}(u, v) = \sum_{h=0}^{3\cdot 2^{n-1}} \sum_{k=0}^{3\cdot 2^{n-1}} F_{hk} u^h v^k$$

symmetric in u and v, with integral coefficients, and with the highest terms $u^{3\cdot 2^{n-1}}$ and $v^{3\cdot 2^{n-1}}$, such that

(8) $$F_{(n)}\big(j(2^n \omega), j(\omega)\big) = 0$$

identically in ω.

We shall establish in this note an upper estimate for the length

(9) $$L_{(n)} = L(F_{(n)})$$

of the polynomial $F_{(n)}(u, v)$, thus for the quantity

$$L_{(n)} = \sum_{h=0}^{3\cdot 2^{n-1}} \sum_{k=0}^{3\cdot 2^{n-1}} |F_{hk}|.$$

The coefficients of $F_{(n)}$ become quickly very large, and such an estimate does not seem to have so far been obtained. The proof will depend on the relation (5) between $j(\omega)$ and $k(\omega)$ and on Gauss's formula (6).

3. Put

$$j(2^h\omega) = j_h \quad \text{and} \quad k(2^h\omega) = k_h \quad (h = 0, 1, 2, \ldots).$$

Firstly, by (5),

$$2^8(k_0^4 - k_0^2 + 1)^3 - j_0 k_0^4 (1 - k_0^2)^2 = 0,$$

or, say,

(10) $$f_{(0)}(j_0, k_0) = 0,$$

where $f_{(0)}(u, v)$ is the polynomial

(11) $$f_{(0)}(u, v) = 2^8(v^4 - v^2 + 1)^3 - uv^4(1 - v^2)^2.$$

By (6), the consecutive function values $k_0, k_1, k_2, \ldots$ are connected by the recursive formulae

(12) $$k_n = 2(k_{n+1})^{1/2}(k_{n+1} + 1)^{-1} \quad (n = 0, 1, 2, \ldots).$$

Let us therefore define a sequence of polynomials $\{f_{(n)}(u, v)\}$ by the formulae

(13)
$$f_{(n+1)}(u, v) = \begin{cases} 2^{-4}(1+v)^{12} f_{(0)}\left(u, \dfrac{2\sqrt{v}}{1+v}\right) & \text{for } n = 0, \\ 2^{-2}(1+v)^{12} f_{(1)}\left(u, \dfrac{2\sqrt{v}}{1+v}\right) & \text{for } n = 1, \\ (1+v)^{2\partial_v(f_{(n)})} f_{(n)}\left(u, \dfrac{2\sqrt{v}}{1+v}\right) f_{(n)}\left(u, -\dfrac{2\sqrt{v}}{1+v}\right) & \text{for } n \geqslant 2. \end{cases}$$

Then

(14)
$$\begin{aligned} f_{(1)}(u, v) &= 2^4(v^4 + 14v^2 + 1)^3 - uv^2(1 - v^2)^2, \\ f_{(2)}(u, v) &= 4(v^4 + 60v^3 + 134v^2 + 60v + 1)^3 - uv(v+1)^2(v-1)^8. \end{aligned}$$

Generally, for all $n \geqslant 2$, $f_{(n)}(u, v)$ becomes a polynomial in u and v with rational integral coefficients, of the form

(15) $$f_{(n)}(u, v) = \sum_{h=0}^{2^{n-2}} \sum_{k=0}^{12\cdot 2^{n-2}} f_{hk}^{(n)} u^h v^k$$

and, naturally, with the property that

(16) $$f_{(n)}(j_0, k_n) = 0.$$

4. Put

$$\Lambda_{(n)} = L(f_{(n)}) \qquad (n = 0, 1, 2, \ldots). \tag{17}$$

Thus, by (11) and (14),

$$\Lambda_{(0)} = 2^8 3^3 + 2^2, \qquad \Lambda_{(1)} = 2^{16} + 2^2, \qquad \Lambda_{(2)} = 2^{26} + 2^4 7. \tag{18}$$

We shall now determine a recursive inequality for $\Lambda_{(n)}$ and by means of it an upper estimate for this quantity.

Let already $n \geqslant 2$. By (13) and (15),

$$f_{(n+1)}(u, v) = (1+v)^{2\cdot 12\cdot 2^{n-2}} \times \\ \times \left\{\sum_{h=0}^{2^{n-2}} \sum_{k=0}^{12\cdot 2^{n-2}} f_{hk}^{(n)} u^h \left(\frac{2\sqrt{v}}{1+v}\right)^k\right\} \left\{\sum_{h=0}^{2^{n-2}} \sum_{k=0}^{12\cdot 2^{n-2}} f_{hk}^{(n)} u^h \left(\frac{-2\sqrt{v}}{1+v}\right)^k\right\}.$$

Here, for both signs $\varepsilon = +1$ and $\varepsilon = -1$,

$$(1+v)^{12\cdot 2^{n-2}} \sum_{h=0}^{2^{n-2}} \sum_{k=0}^{12\cdot 2^{n-2}} f_{hk}^{(n)} u^h \left(\varepsilon \frac{2\sqrt{v}}{1+v}\right)^k = \sum_{h=0}^{2^{n-2}} \sum_{l=0}^{6\cdot 2^{n-2}} f_{h,2l}^{(n)} u^h 2^{2l} v^l (1+v)^{12\cdot 2^{n-2}-2l} + \\ + \varepsilon\sqrt{v} \sum_{h=0}^{2^{n-2}} \sum_{l=0}^{6\cdot 2^{n-2}-1} f_{h,2l+1}^{(n)} u^h 2^{2l+1} v^l (1+v)^{12\cdot 2^{n-2}-2l-1}.$$

Hence $f_{(n+1)}$ has the rational form

$$f_{(n+1)}(u, v) = \left\{\sum_{h=0}^{2^{n-2}} \sum_{l=0}^{6\cdot 2^{n-2}} f_{h,2l}^{(n)} u^h 2^{2l} v^l (1+v)^{12\cdot 2^{n-2}-2l}\right\}^2 - \\ - v \cdot \left\{\sum_{h=0}^{2^{n-2}} \sum_{l=0}^{6\cdot 2^{n-2}-1} f_{h,2l+1}^{(n)} u^h 2^{2l+1} v^l (1+v)^{12\cdot 2^{n-2}-2l-1}\right\}^2.$$

Now

$$L\left(2^k (1+v)^{12\cdot 2^{n-2}-k}\right) = 2^{12\cdot 2^{n-2}} \qquad (k = 0, 1, \ldots, 12\cdot 2^{n-2}).$$

It follows therefore that

$$\Lambda_{(n+1)} \leqslant 2^{2\cdot 12\cdot 2^{n-2}} \left\{\left(\sum_{h=0}^{2^{n-2}} \sum_{l=0}^{6\cdot 2^{n-2}} |f_{h,2l}^{(n)}|\right)^2 + \left(\sum_{h=0}^{2^{n-2}} \sum_{l=0}^{6\cdot 2^{n-2}-1} |f_{h,2l+1}^{(n)}|\right)^2\right\},$$

whence evidently

$$\Lambda_{(n+1)} \leqslant 2^{24\cdot 2^{n-2}} \Lambda_{(n)}^2 \qquad \text{for} \qquad n \geqslant 2. \tag{19}$$

On applying this inequality repeatedly, we find easily that

$$\Lambda_{(n)} \leqslant 2^{12(n-2)2^{n-2}} \Lambda_{(2)}^{2^{n-2}} \qquad \text{for} \qquad n \geqslant 2.$$

Here, by (18),

$$\Lambda_{(2)} < 2^{28},$$

and therefore

(20) $$\Lambda_{(n)} < 2^{(3n+1)2^n} \quad \text{for} \quad n \geqslant 2.$$

This estimate is not valid when $n = 0$ and $n = 1$. It would have some interest to decide whether there exists a positive constant C such that

$$\Lambda_{(n)} \leqslant 2^{C\cdot 2^n}$$

for all sufficiently large n.

5. Let again $n \geqslant 2$. Put

(21) $$a_k^{(n)}(u) = \sum_{h=0}^{2^{n-2}} f_{hk}^{(n)} u^h \qquad (k = 0, 1, \ldots, 12\cdot 2^{n-2}),$$

so that, by (15),

(22) $$f_{(n)}(u, v) = \sum_{k=0}^{12\cdot 2^{n-2}} a_k^{(n)}(u) v^k.$$

Here the $a_k^{(n)}(u)$ are polynomials in u with rational integral coefficients, where the inequality (20) implies that

(23) $$\sum_{k=0}^{12\cdot 2^{n-2}} L(a_k^{(n)}) < 2^{(3n+1)2^n}.$$

Both $a_0^{(n)}(u)$ and $a_{12\cdot 2^{n-2}}^{(n)}(u)$ can be determined explicitly, as follows. Firstly, by (11) and (14),

$$a_0^{(0)}(u) = 2^8, \qquad a_0^{(1)}(u) = 2^4, \qquad a_0^{(2)}(u) = 4,$$

while by (13),

$$a_0^{(n+1)}(u) = f_{(n+1)}(u, 0) = f_{(n)}(u, 0)^2 = a_0^{(n)}(u)^2.$$

It follows therefore that, for all $n \geqslant 2$,

(24) $$a_0^{(n)}(u) = 2^{2^{n-1}},$$

hence that $a_0^{(n)}(u)$ is for all n independent of u.

Next $f_{(n)}(u, v)$ is reciprocal with respect to the variable v,

(25) $$v^{\partial_v(f_{(n)})} f_{(n)}\left(u, \frac{1}{v}\right) = f_{(n)}(u, v),$$

whence also

(26) $$a_k^{(n)}(u) = a_{12\cdot 2^{n-2}}^{(n)}(u) \qquad (k = 0, 1, \ldots, 12\cdot 2^{n-2}).$$

For all three polynomials $f_{(0)}, f_{(1)}$, and $f_{(2)}$ are reciprocal; and if $n \geqslant 2$ and $f_{(n)}$ is reciprocal, then the same is true for $f_{(n+1)}$ because, by (13),

$$\begin{aligned} v^{12\cdot 2^{n-1}} f_{(n+1)}\left(u, \frac{1}{v}\right) \\ &= v^{12\cdot 2^{n-1}}\{1+(1/v)\}^{12\cdot 2^{n-1}} f_{(n)}\left(u, \frac{2v^{-1/2}}{1+v^{-1}}\right) f_{(n)}\left(u, \frac{-2v^{-1/2}}{1+v^{-1}}\right) \\ &= (1+v)^{12\cdot 2^{n-1}} f_{(n)}\left(u, \frac{2\sqrt{v}}{1+v}\right) f_{(n)}\left(u, -\frac{2\sqrt{v}}{1+v}\right) = f_{(n+1)}(u, v). \end{aligned}$$

It follows now from (24) and (26) that also

$$a^{(n)}_{12\cdot 2^{n}-2}(u) = 2^{2^{n-1}} \qquad \text{if} \qquad n \geqslant 2. \tag{27}$$

The term of $f_{(n)}$ of highest degree in v has thus for $n \geqslant 2$ the form

$$2^{2^{n-1}} v^{12\cdot 2^{n-2}}$$

and so is independent of u.

6. The functions

$$j_0 = j(\omega) \qquad \text{and} \qquad k_n = k(2^n\omega)$$

are connected by the equation

$$f_{(n)}(j_0, k_n) = 0. \tag{28}$$

It follows further, from (5), on replacing ω by $2^n\omega$, that

$$j_n = j(2^n\omega) \qquad \text{and} \qquad k_n = k(2^n\omega)$$

satisfy the equation

$$f_{(0)}(j_n, k_n) = 0. \tag{29}$$

Denote therefore by

$$R_{(n)} = R_{(n)}(j_0, j_n)$$

the resultant relative to v of the two polynomials

$$f_{(n)}(j_0, v) = \sum_{k=0}^{12\cdot 2^{n}-2} a_k^{(n)}(j_0) v^k$$

and

$$f_{(0)}(j_n, v) = 2^8(v^4 - v^2 + 1)^3 - j_n v^4 (1 - v^2)^2.$$

This resultant is a polynomial in j_0 and j_n which does not vanish identically. For the coefficients of the highest powers

$$v^{12\cdot 2^{n}-2} \qquad \text{and} \qquad v^{12}$$

of v that occur in these two polynomials are never zero; and whatever the value of v, it is always possible to find a value of j_n such that

$$f_{(0)}(j_n, v) \neq 0.$$

As usual, $R_{(n)}$ can be written as a determinant. For this purpose, let

$$f_{(0)}(j_n, v) = \sum_{k=0}^{12} b_k(j_n) v^k, \tag{30}$$

so that evidently

$$b_0(j_n) = b_{12}(j_n) = 2^8, \quad b_2(j_n) = b_{10}(j_n) = -3\cdot 2^8,$$
$$b_4(j_n) = b_8(j_n) = 6\cdot 2^3 - j_n, \quad b_6(j_n) = -7\cdot 2^8 + 2j_n;$$
$$b_1(j_n) = b_3(j_n) = b_5(j_n) = b_7(j_n) = b_9(j_n) = b_{11}(j_n) = 0.$$

Further

$$\sum_{k=0}^{12} L(b_k) = 2^8 3^3 + 2^2. \tag{31}$$

The resultant $R_{(n)}$ takes now the explicit form

$$R_{(n)}(j_0, j_n) = \begin{vmatrix} a_N^{(n)}(j_0) & a_{N-1}^{(n)}(j_0) & \cdots & a_0^{(n)}(j_0) & 0 & \cdots & 0 \\ 0 & a_N^{(n)}(j_0) & \cdots & a_1^{(n)}(j_0) & a_0^{(n)}(j_0) & \cdots & 0 \\ \vdots & & \ddots & & & \ddots & \vdots \\ 0 & 0 & \cdots & a_N^{(n)}(j_0) & a_{N-1}^{(n)}(j_0) & \cdots & a_0^{(n)}(j_0) \\ b_{12}(j_n) & b_{11}(j_n) & \cdots & b_0(j_n) & 0 & 0 \;\cdots & 0 \\ 0 & b_{12}(j_n) & \cdots & b_1(j_n) & b_0(j_n) & 0 & 0 \\ \vdots & & \ddots & & & \ddots & \vdots \\ 0 & 0 & \cdots & b_{12}(j_n) & b_{11}(j_n) & \cdots & b_0(j_n) \end{vmatrix} \begin{matrix} \left.\vphantom{\begin{matrix}a\\a\\a\\a\end{matrix}}\right\} 12 \text{ rows} \\ \left.\vphantom{\begin{matrix}a\\a\\a\\a\end{matrix}}\right\} N \text{ rows} \end{matrix} \tag{32}$$

where N stands for the abbreviation

$$N = 12\cdot 2^{n-2}.$$

We apply now the following trivial estimate for the length of a determinant. Let

$$p_{hk}(u, v) \quad (h, k = 1, 2, \ldots, m)$$

be arbitrary polynomials with complex coefficients in any two indeterminates u and v, and let $D(u, v)$ be the determinant

$$D = \begin{vmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \cdot & \cdot & \cdot & \cdot \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{vmatrix}.$$

It is then evident from the definition of a determinant that

$$L(D) \leqslant \prod_{h=1}^{m} \bigl(L(p_{h1}) + L(p_{h2}) + \ldots + L(p_{hm})\bigr).$$

On applying this inequality to the determinant for $R_{(n)}$ and making use of the estimates (23) and (31), noting that

$$2^8 3^3 + 2^2 < 2^{13},$$

we find that

$$L(R_{(n)}) < 2^{12(3n+1)2^n} (2^8 3^3 + 2^2)^{12\cdot 2^{n-2}}$$

and hence that

$$L(R_{(n)}) < 2^{(36n+51)\cdot 2^n}. \tag{33}$$

In the determinant for $R_{(n)}$, the elements $a_k^{(n)}(j_0)$ are polynomials in j_0 at most of degree 2^{n-2}, while the elements $b_k(j_n)$ are polynomials in j_n at most of degree 1, where all these polynomials have rational integral coefficients. Therefore $R_{(n)}(j_0, j_n)$ is a polynomial with rational integral coefficients in j_0 and j_n, at most of degree $12\cdot 2^{n-2}$ in j_0 and at most of degree $12\cdot 2^{n-2}$ in j_n. Hence, in the notation of § 1,

$$\Delta(R_{(n)}) \leqslant 24\cdot 2^{n-2}. \tag{34}$$

7. The two equations (28) and (29) can only hold if

$$R_{(n)}(j_0, j_n) = 0.$$

On the other hand, j_0 and j_n are also connected by the transformation equation

$$F_{(n)}(j_0, j_n) = 0,$$

and it is known that the polynomial $F_{(n)}(u, v)$ is irreducible. Hence the polynomial $R_{(n)}(u, v)$ necessarily is divisible by $F_{(n)}(u, v)$. The latter polynomial is primitive because its highest coefficients are equal to 1. Therefore $R_{(n)}$ allows a factorisation

$$R_{(n)}(u, v) = F_{(n)}(u, v) G_{(n)}(u, v)$$

where $G_{(n)}$ denotes a further polynomial in u and v with rational integral coefficients. Therefore

$$L(G_{(n)}) \geqslant 1. \tag{35}$$

The inequality (2) implies then that

$$L(F_{(n)}) \leqslant L(F_{(n)}) L(G_{(n)}) \leqslant 2^{\Delta(R_{(n)})} L(R_{(n)}),$$

hence, by (33) and (35),

$$L(F_{(n)}) \leqslant 2^{24\cdot 2^{n-2}} \cdot 2^{(36n+51)2^n}.$$

Thus we arrive finally at the following result.

THEOREM. *For every positive integer n, the length $L(F_{(n)})$ of the 2^nth transformation polynomial $F_{(n)}(u, v)$ satisfies the inequality*

$$L(F_{(n)}) \leqslant 2^{(36n+57)2^n}. \tag{36}$$

Actually, our proof gave this estimate only for $n \geqslant 2$. It remains, however, true also for $n = 1$ because the explicit expression for $F_{(1)}(u, v)$ shows that

$$L(F_{(1)}) < 2^{48}.$$

It would be valuable if it could be proved that $L(F_{(n)})$ satisfies a stronger inequality

$$L(F_{(n)}) \leqslant 2^{C\cdot 2^n}$$

where C denotes any absolute positive constant. For such a result would enable one to prove that

$$j\left(\frac{\log q}{\pi i}\right)$$

is transcendental for all algebraic numbers q satisfying

$$0 < |q| < 1.$$

It is, as yet, unknown whether this statement is in fact true.

References

[1] K. Mahler, *On some inequalities for polynomials in several variables*, J. London Math. Soc. 37 (1962), pp. 341–344.

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