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SUPERSINGULAR j-INVARIANTS AS SINGULAR MODULI MOD p

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1. Introduction. In this paper we shall give some results concerned with the reduction modulo p of the minimal polynomials of "singular moduli". Let $O_D=\boldsymbol{Z}\left[\frac{1}{2}(D+\sqrt{-D})\right]$ be the imaginary quadratic order of discriminant $-D$ ($D\equiv 0,3 \bmod 4$). We denote by $P_D(X)$ the monic polynomial whose roots are precisely the distinct j-invariants of elliptic curves over $\bar{\boldsymbol{Q}}$ with complex multiplication by O_D ($\bar{\boldsymbol{Q}}$ is the algebraic closure of the rationals $\boldsymbol{Q}$). It is well known that $P_D(X)$ has its coefficients in the ring of integers $\boldsymbol{Z}$ and the degree of $P_D(X)$ is equal to the class number of O_D. Let E be an elliptic curve defined over $\boldsymbol{Q}$ and $J=j(E)$ be its j-invariant. As was observed by N. Elkies in [5], if a prime factor p of the numerator of $P_D(J)$ satisfies $\left(\frac{\boldsymbol{Q}(\sqrt{-D})}{p}\right)\neq 1$ (i.e., p does not split completely in $\boldsymbol{Q}(\sqrt{-D})$), then (provided that E has good reduction at p) p is supersingular for E. Conversely, every supersingular prime p for E appears as a prime factor of the numerator of $P_D(J)$ for some D with $\left(\frac{\boldsymbol{Q}(\sqrt{-D})}{p}\right)\neq 1$. Elkies pointed out that, for supersingular p, such D can always be found within the bound $D<2p^{2/3}$. Furthermore he made an observation that such bound seemed to be in no way best possible. The first purpose of this paper is to give a better bound $D\leq\frac{4}{\sqrt{3}}\sqrt{p}$, which is a consequence of the following

Theorem 1. *Every supersingular j-invariant contained in the prime field $\boldsymbol{F}_p$ is a root of some $P_D(X)$* mod p *with* $D\leq\frac{4}{\sqrt{3}}\sqrt{p}$.

Here we recall that supersingular j-invariants in characteristic p are all contained in $\boldsymbol{F}_{p^2}$ (the field with p^2 elements) and some of them are in $\boldsymbol{F}_p$ whose cardinality is related to the class number of the field $\boldsymbol{Q}(\sqrt{-p})$. As our E is defined over $\boldsymbol{Q}$, $j(E)$ mod p is contained in $\boldsymbol{F}_p$.

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Our next theorem concerns common roots of two polynomials $P_{D_1}(X)$ mod p and $P_{D_2}(X)$ mod p.

Theorem 2. *If two different discriminants $-D_1$ and $-D_2$ satisfy $D_1 D_2<4p$ (in particular $D_1, D_2<2\sqrt{p}$), then two polynomials $P_{D_1}(X)$ mod p and $P_{D_2}(X)$ mod p in $\boldsymbol{F}_p[X]$ have no roots in common. In other words, every prime factor p of the resultant of $P_{D_1}(X)$ and $P_{D_2}(X)$ satisfies $p\leq\frac{D_1 D_2}{4}$.*

Furthermore, if $\boldsymbol{Q}(\sqrt{-D_1})=\boldsymbol{Q}(\sqrt{-D_2})$, the above inequality $D_1 D_2<4p$ $\left(\text{resp. } p\leq\frac{D_1 D_2}{4}\right)$ can be replaced by $D_1 D_2<p^2$ (resp. $p\leq\sqrt{D_1 D_2}$).

As our proof will show, each prime factor p of the resultant of $P_{D_1}(X)$ and $P_{D_2}(X)$ divides a positive integer of the form $(D_1 D_2-x^2)/4$. When D_1 and D_2 are fundamental discriminants and relatively prime, this fact was given by B. Gross and D. Zagier in [6] as a corollary of their explicit prime factorization of the resultant of $P_{D_1}(X)$ and $P_{D_2}(X)$.

By Deuring's theory of reduction of elliptic curves, Theorem 2 can be reformulated as the following Theorem 2′ which is a little more general than a theorem of Eichler [3] but the proof is essentially the same. Let $Q_{\infty,p}$ be the definite quaternion algebra over $\boldsymbol{Q}$ which ramifies only at p. The order O_D is said to be optimally embedded in a maximal order R of $Q_{\infty,p}$ if $\boldsymbol{Q}(\sqrt{-D})$ embeds into $Q_{\infty,p}$ and $R\cap\boldsymbol{Q}(\sqrt{-D})=O_D$.

Theorem 2′. *Suppose that two quadratic orders O_{D_1} and O_{D_2} are optimally embedded in a maximal order of $Q_{\infty,p}$ with different images, then the inequality $D_1 D_2\geq 4p$ holds. If $\boldsymbol{Q}(\sqrt{-D_1})=\boldsymbol{Q}(\sqrt{-D_2})$, this inequality can be replaced by $D_1 D_2\geq p^2$.*

In the appendix, we shall give an alternative proof of a proposition by Elkies [5] which was crucial for his proof of the infinitude of supersingular primes for elliptic curves over $\boldsymbol{Q}$.

The author is very grateful to Professor T. Ibukiyama for his helpful communications. The constant of our Theorem 1 was improved to the present form by his remark.

2. Proof of Theorem 1. Let E be an arbitrary supersingular elliptic curve defined over $\boldsymbol{F}_p$ (hence its j-invariant is contained in $\boldsymbol{F}_p$) and End E its endomorphism ring over the algebraic closure of $\boldsymbol{F}_p$. To prove Theorem 1, it suffices to show that End E contains an order O_D with $D\leq\frac{4}{\sqrt{3}}\sqrt{p}$. For, if an order O_D is contained in End E, by Deuring's Lifting Lemma ([2, p. 259]), there exists an elliptic curve over $\bar{\boldsymbol{Q}}$ with complex multiplication by some order $O_{D'}$

containing O_D whose reduction to characteristic p is isomorphic to E. Then the j-invariant of E is a root of $P_{D'}(X)$ mod p with $D' \leq D \leq \frac{4}{\sqrt{3}}\sqrt{p}$ and Theorem 1 follows. It is well known that, when E is defined over $\boldsymbol{F}_p$, End E is isomorphic to a maximal order of $Q_{\infty,p}$ which contains an element with the minimal polynomial X^2+p (Frobenius element). On the other hand, such a maximal order has been described explicitly by Ibukiyama in [7] as follows. Choose a prime q such that $q \equiv 3$ mod 8 and $\left(\frac{-p}{q}\right)=1$. Here, $\left(\frac{-p}{q}\right)$ is the Legendre's symbol. Then $Q_{\infty,p}$ can be realized as

$$Q_{\infty,p} = \boldsymbol{Q}+\boldsymbol{Q}\alpha+\boldsymbol{Q}\beta+\boldsymbol{Q}\alpha\beta\,,$$

where $\alpha^2=-p$, $\beta^2=-q$, and $\alpha\beta=-\beta\alpha$. Choosing an integer r such that $r^2+p \equiv 0$ mod q, put

$$O(q,r) = \boldsymbol{Z}+\boldsymbol{Z}\frac{1+\beta}{2}+\boldsymbol{Z}\frac{\alpha(1+\beta)}{2}+\boldsymbol{Z}\frac{(r+\alpha)\beta}{q}\,.$$

When $p \equiv 3$ mod 4, we further choose an integer r' such that $r'^2+p \equiv 0$ mod $4q$ and put

$$O'(q,r')=\boldsymbol{Z}+\boldsymbol{Z}\frac{1+\alpha}{2}+\boldsymbol{Z}\beta+\boldsymbol{Z}\frac{(r'+\alpha)\beta}{2q}\,.$$

Then a part of Ibukiyama's results says that both $O(q,r)$ and $O'(q,r')$ (their isomorphism classes depend only on q not on r nor r') are maximal orders of $Q_{\infty,p}$ and any maximal order which contains an element with the minimal polynomial X^2+p is isomorphic to $O(q,r)$ or $O'(q,r')$ with suitable choise of q. Therefore our task is to show that for any q both $O(q,r)$ and $O'(q,r')$ contain an element $\frac{1}{2}(D+\sqrt{-D})$ (i.e., an element with the minimal polynomial $X^2-DX+\frac{1}{4}(D^2+D)$) with $D \leq \frac{4}{\sqrt{3}}\sqrt{p}$.

We start with $O(q,r)$. Let

$$\gamma = w+x\frac{1+\beta}{2}+y\frac{\alpha(1+\beta)}{2}+z\frac{(r+\alpha)\beta}{q}$$

denote an element in $O(q,r)$ ($w, x, y, z \in \boldsymbol{Z}$) and consider the following diophantine equations:

$$tr(\gamma) = 2w+x = D$$

and

$$n(\gamma) = \left(w+\frac{x}{2}\right)^2+\frac{p}{4}y^2+q\left(\frac{x}{2}+\frac{zr}{q}\right)^2+pq\left(\frac{y}{2}+\frac{z}{q}\right)^2 = \frac{D^2+D}{4}\,,$$

where $tr(\gamma)$ (resp. $n(\gamma)$) is the reduced trace (resp. norm) of γ. These equations are equivalent to

$$2w+x=D\,, \tag{2–1}$$

$$py^2+q\left(x+\frac{2zr}{q}\right)^2+pq\left(y+\frac{2z}{q}\right)^2=D\,. \tag{2–2}$$

Note that, by our choise of q and r, for any x, y, z in $\boldsymbol{Z}$ the left hand side of (2–2) always represent an integer congruent modulo 2 to x. So, if integers x, y and z satisfies (2–2), we can always find an integer w which satisfies (2–1). Therefore, the problem is to find such D not greater than $\frac{4}{\sqrt{3}}\sqrt{p}$ that the equation (2–2) is soluble. Now, if we put $y=0$ in (2–2), we have

$$\frac{(qx+2zr)^2+4pz^2}{q}=D \tag{2–3}$$

and the left hand side of (2–3) is a positive definite binary quadratic form in x and z with determinant $4p$. Hence a classical theorem (cf. e.g. [1, p. 30]) assures that there exists integers x and z so that the left hand side of (2–3) is less than or equal to $\sqrt{\frac{4\times 4p}{3}}=\frac{4}{\sqrt{3}}\sqrt{p}$. This proves our assertion.

As for $O'(q, r')$ (when $p\equiv 3 \bmod 4$), the same calculations will do. Put

$$\gamma=w+x\,\frac{1+\alpha}{2}+y\beta+z\,\frac{(r'+\alpha)\,\beta}{2q}\in O'(q, r')\,.$$

From the conditions $tr(\gamma)=D$ and $n(\gamma)=\frac{D^2+D}{4}$ we have

$$2w+x=D \tag{2–4}$$

$$px^2+q\left(2y+\frac{zr'}{q}\right)^2+\frac{pz^2}{q}=D\,. \tag{2–5}$$

As before, for any x, y, z in $\boldsymbol{Z}$ the left hand side of (2–5) is an integer congruent modulo 2 to x and hence the w determined by (2–4) is in $\boldsymbol{Z}$. Again by putting $x=0$ the left hand side of (2–5) is a positive definite binary quadratic form of determinant $4p$. Therefore there exists an element $\gamma\in O'(q, r')$ whose minimal polynomial is $X^2-DX+\frac{1}{4}(D^2+D)$ with $D\leq\frac{4}{\sqrt{3}}\sqrt{p}$. This concludes our proof of Theorem 1.

3. Proof of Theorem 2′. Suppose that O_{D_1} and O_{D_2} are optimally embedded in a maximal order R of $Q_{\infty,p}$ with different images. Let α_i ($i=1, 2$) be the images of $\frac{1}{2}(D_i+\sqrt{-D_i})$ by these embeddings ($\alpha_1\neq\alpha_2$). In R, consider the $\boldsymbol{Z}$-module L generated by 1, α_1, α_2, and $\alpha_1\alpha_2$. In general, a module $\boldsymbol{Z}\mu_1+$

$\boldsymbol{Z}\mu_2+\boldsymbol{Z}\mu_3+\boldsymbol{Z}\mu_4$ in $Q_{\infty,p}$ has rank 4 if and only if its discriminant $D(\mu_1, \mu_2, \mu_3, \mu_4)$ $=det(tr(\mu_i\, \mu_j))$ is not euqal to 0 (cf. e.g. [3, Ch. 1 §2 Th. 1]). As for our L we have by a direct calculation

$$D(1, \alpha_1, \alpha_2, \alpha_1\, \alpha_2) = -\left\{\frac{D_1\, D_2-(2s-D_1\, D_2)^2}{4}\right\}^2,$$

where $s=tr(\alpha_1\alpha_2)\,(\in\boldsymbol{Z})$. Now consider the element $\beta=\left(\alpha_1-\frac{D_1}{2}\right)\left(\alpha_2-\frac{D_2}{2}\right)$ in R. It does not belong to $\boldsymbol{Q}$ (the center of $Q_{\infty,p}$) even when $\boldsymbol{Q}(\sqrt{-D_1})=\boldsymbol{Q}(\sqrt{-D_2})$ because of our assumption that O_{D_1} and O_{D_2} are optimally embedded with different images. Hence

$$\begin{aligned} tr(\beta)^2-4n(\beta) &= \left(s-\frac{D_1\, D_2}{2}\right)^2-4\times\frac{D_1\, D_2}{16} \\ &= \frac{(2s-D_1\, D_2)^2-D_1\, D_2}{4}<0\,. \end{aligned}$$

Therefore, we have $D(1, \alpha_1, \alpha_1, \alpha_1\, \alpha_2)\neq 0$. On the other hand, we can readily show that L is a subring (α_i^2, $\alpha_2\, \alpha_1\in L$ etc.) of R. Hence we conclude that L is an order of $Q_{\infty,p}$. As the discriminant of an order in $Q_{\infty,p}$ is divisible by p^2 (the discriminant of maximal orders), we conclude that p divides the positive integer $\frac{1}{4}(D_1\, D_2-(2s-D_1\, D_2)^2)$, in particular $p\leq\frac{D_1\, D_2}{4}$.

When D_1 and D_2 are given as $D_1=f_1^2\, D$ and $D_2=f_2^2\, D$ with positive integers f_1, f_2, D, we have

$$\frac{D_1 D_2-(2s-D_1 D_2)^2}{4}=\frac{(f_1 f_2 D-(2s-D_1 D_2))\,(f_1 f_2 D+(2s-D_1 D_2))}{4}(>0)\,.$$

As the inequality $|\, f_1 f_2 D\pm(2s-D_1 D_2)\,|\leq 2f_1 f_2 D$ holds and both $f_1 f_2 D-(2s-D_1 D_2)$ and $f_1 f_2 D-(2s-D_1 D_2)$ are even numbers (since they have same parity and their product is divisible by 4), we must have $p\leq f_1 f_2 D=\sqrt{D_1\, D_2}$. This completes our proof.

Appendix. An alternative proof of a proposition in [5][2]. Let p be a prime number. Recall that $P_D(X)$ denotes the minimal polynomial of a singular modulus having O_D as complex multiplication. In [5] the following proposition played an essential role.

Proposition (Elkies). *Assume* $p\equiv 3$ (*mod* 4). *We have*

$$\begin{aligned} P_p(X) &\equiv (X-12^3)\,(R(X))^2 \mod p \\ P_{4p}(X) &\equiv (X-12^3)\,(S(X))^2 \mod p \end{aligned}$$

2 N. Elkies informed the author that the following proof had also been discovered by D. Zagier.

with some polynomials $R(X)$, $S(X)\in \mathbf{Z}[X]$.

We shall give a proof of this proposition by using two classical results due to Kronecker. First we shall prove the following Proposition′. (Actually in this form Elkies used the proposition.)

Proposition′. *We have*

$$P_p(X)\equiv (T(X))^2 \bmod p \quad \text{if} \quad p\equiv 1\,(4),$$
$$P_p(X)\,P_{4p}(X)\equiv (U(X))^2 \bmod p \quad \text{if} \quad p\equiv 3\,(4)$$

with some polynomials $T(X)$, $U(X)\in \mathbf{Z}[X]$.

Proof. Let $\Phi_p(X, Y)$ denote the p-th modular polynomial. (cf. [8, Ch. 5 §2]) The following two properties on $\Phi_p(X, Y)$ are known as the "Kronecker's relations":

(4–1) $$\Phi_p(X, Y)\equiv (X^p-Y)(X-Y^p) \bmod p,$$

(4–2) $$\Phi_p(X, X)=-\prod_D P_D(X)^{r(D)} = \begin{cases} -P_{4p}(X)\prod_{p\nmid D} P_D(X)^2 & \text{if} \quad p\equiv 1\,(4) \\ -P_p(X)\,P_{4p}(X)\prod_{p\nmid D} P_D(X)^2 & \text{if} \quad p\equiv 3\,(4), \end{cases}$$

where the product runs over such D that the order O_D contains an element of norm p and $r(D)=1$ or 2 according as $p\,|\,D$ or $p\nmid D$ (cf. [8, Ch. 5 §2 and Ch. 10 App.]) By putting $Y=X$ in (4–1) we get

(4–3) $$\Phi_p(X, X)\equiv -(X^p-X)^2 \bmod p.$$

Proposition′ follows immediately from this and (4–2).

Proof of Proposition. The above relations (4–2) and (4–3) shows that, modulo p, the polynomial $P_p(X)\,P_{4p}(X)$ is a square and divides $(X^p-X)^2$. Hence each of its roots has multiplicity 2. By Lemma 1 in [5], both $P_p(X)$ mod p and $P_{4p}(X)$ mod p have 12^3 as one of their roots. On the other hand, a lemma of Ibukiyama ([7, Lem. 1.8]) implies that there are no other common roots of $P_p(X)$ mod p and $P_{4p}(X)$ mod p. Therefore the conclusion follows.

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