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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  $O_D = \mathbf{Z} \left[ \frac{1}{2}(D + \sqrt{-D}) \right]$  be the imaginary quadratic order of discriminant  $-D$  ( $D \equiv 0, 3 \pmod{4}$ ). We denote by  $P_D(X)$  the monic polynomial whose roots are precisely the distinct  $j$ -invariants of elliptic curves over  $\bar{\mathbf{Q}}$  with complex multiplication by  $O_D$  ( $\bar{\mathbf{Q}}$  is the algebraic closure of the rationals  $\mathbf{Q}$ ). It is well known that  $P_D(X)$  has its coefficients in the ring of integers  $\mathbf{Z}$  and the degree of  $P_D(X)$  is equal to the class number of  $O_D$ . Let  $E$  be an elliptic curve defined over  $\mathbf{Q}$  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  $\left( \frac{\mathbf{Q}(\sqrt{-D})}{p} \right) \neq 1$  (i.e.,  $p$  does not split completely in  $\mathbf{Q}(\sqrt{-D})$ ), 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  $\left( \frac{\mathbf{Q}(\sqrt{-D})}{p} \right) \neq 1$ . 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  $\mathbf{F}_p$  is a root of some  $P_D(X) \pmod{p}$  with  $D \leq \frac{4}{\sqrt{3}}\sqrt{p}$ .*

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

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

**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  $P_{D_1}(X) \bmod p$  and  $P_{D_2}(X) \bmod p$  in  $\mathbf{F}_p[X]$  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  $\mathbf{Q}(\sqrt{-D_1}) = \mathbf{Q}(\sqrt{-D_2})$ , the above inequality  $D_1 D_2 < 4p$  (resp.  $p \leq \frac{D_1 D_2}{4}$ ) 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  $\mathbf{Q}$  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  $\mathbf{Q}(\sqrt{-D})$  embeds into  $Q_{\infty, p}$  and  $R \cap \mathbf{Q}(\sqrt{-D}) = O_D$ .

**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  $\mathbf{Q}(\sqrt{-D_1}) = \mathbf{Q}(\sqrt{-D_2})$ , 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  $\mathbf{Q}$ .

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  $\mathbf{F}_p$  (hence its  $j$ -invariant is contained in  $\mathbf{F}_p$ ) and  $\text{End } E$  its endomorphism ring over the algebraic closure of  $\mathbf{F}_p$ . To prove Theorem 1, it suffices to show that  $\text{End } E$  contains an order  $O_D$  with  $D \leq \frac{4}{\sqrt{3}}\sqrt{p}$ . For, if an order  $O_D$  is contained in  $\text{End } E$ , by Deuring's Lifting Lemma ([2, p. 259]), there exists an elliptic curve over  $\bar{\mathbf{Q}}$  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  $P_{D'}(X) \bmod p$  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  $\mathbf{F}_p$ ,  $\text{End } E$  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  $q \equiv 3 \pmod{8}$  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

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

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

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

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

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

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 choice 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  $O(q, r)$  ( $w, x, y, z \in \mathbf{Z}$ ) and consider the following diophantine equations:

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

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  $\gamma$ . These equations are equivalent to

$$(2-1) \quad 2w+x = D,$$

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

Note that, by our choice of  $q$  and  $r$ , for any  $x, y, z$  in  $\mathbb{Z}$  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

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

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  $p \equiv 3 \pmod{4}$ ), 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

$$(2-4) \quad 2w+x = D$$

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

As before, for any  $x, y, z$  in  $\mathbb{Z}$  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  $\mathbb{Z}$ . 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  $\alpha_i$  ( $i=1, 2$ ) be the images of  $\frac{1}{2}(D_i + \sqrt{-D_i})$  by these embeddings ( $\alpha_1 \neq \alpha_2$ ). In  $R$ , consider the  $\mathbb{Z}$ -module  $L$  generated by 1,  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_1\alpha_2$ . In general, a module  $\mathbb{Z}\mu_1 +$

$\mathbf{Z}\mu_2 + \mathbf{Z}\mu_3 + \mathbf{Z}\mu_4$  in  $Q_{\infty, p}$  has rank 4 if and only if its discriminant  $D(\mu_1, \mu_2, \mu_3, \mu_4) = \det(\text{tr}(\mu_i \mu_j))$  is not equal 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  $s = \text{tr}(\alpha_1 \alpha_2)$  ( $\in \mathbf{Z}$ ). 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  $\mathbf{Q}$  (the center of  $Q_{\infty, p}$ ) even when  $\mathbf{Q}(\sqrt{-D_1}) = \mathbf{Q}(\sqrt{-D_2})$  because of our assumption that  $O_{D_1}$  and  $O_{D_2}$  are optimally embedded with different images. Hence

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

Therefore, we have  $D(1, \alpha_1, \alpha_2, \alpha_1 \alpha_2) \neq 0$ . On the other hand, we can readily show that  $L$  is a subring ( $\alpha_1^2, \alpha_2, \alpha_1 \in L$  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]<sup>2</sup>.** 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  $p \equiv 3 \pmod{4}$ . We have*

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

<sup>2</sup> 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*

$$P_p(X) \equiv (T(X))^2 \pmod{p} \quad \text{if } p \equiv 1 \pmod{4},$$

$$P_p(X) P_{4p}(X) \equiv (U(X))^2 \pmod{p} \quad \text{if } p \equiv 3 \pmod{4}$$

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”:

$$(4-1) \quad \Phi_p(X, Y) \equiv (X^p - Y)(X - Y^p) \pmod{p},$$

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

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

$$(4-3) \quad \Phi_p(X, X) \equiv -(X^p - X)^2 \pmod{p}.$$

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  $P_p(X) \pmod{p}$  and  $P_{4p}(X) \pmod{p}$  have 12<sup>3</sup> 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  $P_p(X) \pmod{p}$  and  $P_{4p}(X) \pmod{p}$ . Therefore the conclusion follows.

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