§4. The case p5

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(3) E has split multiplicative reduction at $3 \Leftrightarrow a_1^2 + a_2 \equiv 1 \pmod 3$.
(4) E has non-split multiplicative reduction at $3 \Leftrightarrow a_1^2 + a_2 \equiv -1 \pmod 3$.

Proof:

$$c_4 \equiv b_2^2 - 24 b_4 \equiv b_2^2 \equiv (a_1^2 + 4a_2)^2 \equiv (a_1^2 + a_2)^2 \pmod 3.$$

The theorem then follows immediately from formula (3.1) and Corollary 1.2.

Remark. $C_2^2 \equiv c_4 \pmod 3$. Note that $C_2 = a_1^2 + a_2$ is a more sensitive invariant than c_4 in that the residue class of C_2 modulo 3 allows us to distinguish between split and non-split multiplicative reduction, while c_4 does not allow us to separate these two possibilities.

§4. The case $p \geqslant 5$

Assume $p \geqslant 5$. Then there exists a minimal Weierstrass equation for E at p of the form

$$Y^2 = X^3 + AX + B \tag{4.1}$$

with A, $B \in \mathbf{Z}$. The coefficient C_{p-1} modulo p is given by Deuring's classical formula [1]

$$C_{p-1} \equiv \sum_{2h+3i=P} \frac{P!}{i!\ h!\ (P-h-i)!} A^h B^i \pmod p \tag{4.2}$$

where $P = (1/2)(p-1)$.

Let $S = (x, y)$ be the singular point on the reduced curve with $x, y \in \mathbf{Z}/p\mathbf{Z}$. The tangents at S are given by a quadratic polynomial $R(T)$ as follows: Transform the curve by $X \to (X+x)$, $Y \to (Y+y)$ so that the singularity is now at (0, 0). The tangents are given by a homogeneous form of degree 2 in X and Y which we can consider as a quadratic polynomial $R(T)$ with $T = Y/X$. Let D be the discriminant of $R(T)$, and let $\left(\frac{\ }{p}\right)$ denote the Legendre symbol with respect to p. We have the following results directly from the definitions.

Proposition 4.1. Assume E has bad reduction at p.

(1) E has additive reduction at $p \Leftrightarrow f_p = 0 \Leftrightarrow S$ is a cusp $\Leftrightarrow R(T)$ has two identical roots over $\mathbf{Z}/p\mathbf{Z} \Leftrightarrow D = 0 \Leftrightarrow \left(\frac{D}{p}\right) = 0$.

(2) E has split multiplicative reduction at $p \Leftrightarrow f_p = 1 \Leftrightarrow S$ is a node with rational tangents $\Leftrightarrow R(T)$ has two distinct roots rational over $\mathbf{Z}/p\mathbf{Z} \Leftrightarrow \left(\frac{D}{p}\right) = 1$.

(3) E has non-split multiplicative reduction at $p \Leftrightarrow f_p = -1 \Leftrightarrow S$ is a node with irrational tangents $\Leftrightarrow R(T)$ has two distinct roots not rational over $\mathbf{Z}/p\mathbf{Z} \Leftrightarrow \left(\frac{D}{p}\right) = -1$.

COROLLARY 4.2. $f_p = \left(\frac{D}{p}\right)$.

In this case, H reduces to

$$H = Y^2 - X^3 - AX - B \tag{4.3}$$

Then we have

$$\partial H/\partial X = -3X^2 - A \tag{4.4}$$

$$\partial H/\partial Y = 2Y \tag{4.5}$$

From (4.5) we must have $y = 0$. From (4.4) we must have $x^2 = -A/3$ in $\mathbf{Z}/p\mathbf{Z}$, so that $-A/3$ is either a quadratic residue modulo p or 0 modulo p. Note that $x = 0 \Leftrightarrow A \equiv 0 \pmod{p}$. Let $X^3 + AX + B = (X-\alpha_1)(X-\alpha_2)(X-\alpha_3)$ be a factorization over $\mathbf{Z}/p\mathbf{Z}$. At least two of $\alpha_1, \alpha_2, \alpha_3$ must coincide with x, let us say $x = \alpha_2 = \alpha_3$. Then

$$X^3 + AX + B = X^3 + (-\alpha_1 - 2\alpha_2)X^2 + (2\alpha_1\alpha_2 + \alpha_2^2)X - \alpha_1\alpha_2^2 \tag{4.6}$$

Thus comparing coefficients, we have

$$0 = -\alpha_1 - 2\alpha_2 \tag{4.7}$$

$$A = 2\alpha_1\alpha_2 + \alpha_2^2 \tag{4.8}$$

$$B = -\alpha_1\alpha_2^2 \tag{4.9}$$

Hence

$$\alpha_1 = -2\alpha_2 \tag{4.10}$$

$$A = 2\alpha_1\alpha_2 + \alpha_2^2 = -3\alpha_2^2 = -3x^2 \tag{4.11}$$

$$B = -\alpha_1\alpha_2^2 = 2\alpha_2^3 = 2x^3 \tag{4.12}$$

From (4.12) we see that $B/2$ is either a cubic residue modulo p or 0 modulo p. Note that $x = 0 \Leftrightarrow B \equiv 0 \pmod{p}$ from (4.12).

Transform the curve by $X \to (X+\alpha_2)$, $Y \to Y$ so that the singular point $S = (x, y) = (x, 0) = (\alpha_2, 0)$ goes to $(0, 0)$. We obtain

$$(4.13) \qquad Y^2 - (X+\alpha_2)^3 - A(X+\alpha_2) - B = Y^2 - X^3 - 3\alpha_2 X^2$$

The tangents to $(0, 0)$ on the transformed curve are given by

$$(4.14) \qquad Y^2 - 3\alpha_2 X^2 = 0$$

so that the polynomial $R(T)$ is $R(T) = T^2 - 3\alpha_2$. $D = 12\alpha_2 = 12x$.

$$c_4 = b_2^2 - 24b_4 = (a_1^2 + 4a_2)^2 - 24(a_1a_3 + 2a_4) = -48A .$$

Since

$$x = 0 \Leftrightarrow A \equiv 0 \pmod{p}, \quad D = 0 \Leftrightarrow A \equiv 0$$

and so the invariant c_4 is enough to distinguish between additive and multiplicative reduction. However, as we shall see below it does not separate split and non-split multiplicative reduction.

THEOREM 4.3. Assume that E has bad reduction at p.

(1) E has additive reduction at $p \Leftrightarrow A \equiv 0 \pmod{p} \Leftrightarrow B \equiv 0 \pmod{p}$ $\Leftrightarrow \left(\frac{-2AB}{p}\right) = 0.$

(2) E has split multiplicative reduction at $p \Leftrightarrow \left(\frac{-2AB}{p}\right) = 1.$

(3) E has non-split multiplicative reduction at $p \Leftrightarrow \left(\frac{-2AB}{p}\right) = -1.$

Proof: (1) We have seen that $A \equiv 0 \pmod{p} \Leftrightarrow x = 0 \Leftrightarrow B \equiv 0 \pmod{p}$. E has additive reduction at $p \Leftrightarrow D = 12x = 0 \Leftrightarrow x = 0$ $\Leftrightarrow A \equiv B \equiv 0 \pmod{p} \Leftrightarrow \left(\frac{-2AB}{p}\right) = 0.$

(2) and (3). Assume E has multiplicative reduction at p. Then $3\alpha_2 \neq 0$. From (4.14) we see that E has split multiplicative reduction at $p \Leftrightarrow 3\alpha_2$ is a square in $\mathbf{Z}/p\mathbf{Z}$. From formulas (4.11) and (4.12) we have that $3\alpha_2 = (-9/2)\, B/A$. Thus $3\alpha_2$ is a square $\Leftrightarrow (-9/2)\, B/A$ is a square modulo p $\Leftrightarrow -2AB$ is a square modulo $p \Leftrightarrow \left(\frac{-2AB}{p}\right) = 1.$

COROLLARY 4.4. $f_p = \left(\frac{-2AB}{p}\right).$