Elliptic Curves - Example Sheet 3

1 (i) $y^2+xy = x^3+1$

$p=2$: $x=0 \Rightarrow y=1$; $x=1 \Rightarrow y=0$ or 1 $\Rightarrow \#\tilde{E}(\mathbb{F}_2)=4$

$p=3$:

x	-1	0	1
x^3+x^2+x+1	0	①	①

$\Rightarrow \#\tilde{E}(\mathbb{F}_3)=6$

$p=5$:

x	-2	-1	0	1	2
x^3-x^2-2x+1	3	①	①	④	①

$\Rightarrow \#\tilde{E}(\mathbb{F}_5)=9$

$p=7$:

x	-3	-2	-1	0	1	2	3
x^3+2x^2-2x+1	5	5	④	①	②	6	5

$\Rightarrow \#\tilde{E}(\mathbb{F}_7)=7$

(ii) Taking $p=2$ & $p=5$ gives
$\#E(\mathbb{Q})_{tors} \mid 2^a$ some $a \geq 0$
$\#E(\mathbb{Q})_{tors} \mid 9.5^b$ some $b \geq 0$
$\Rightarrow E(\mathbb{Q})_{tors} = 0$

(iii)
$$E_2(\mathbb{Q}_2) \subset E_1(\mathbb{Q}_2) \subset E_0(\mathbb{Q}_2) = E(\mathbb{Q}_2)$$

$E_2(\mathbb{Q}_2)$: quotient $(\mathbb{F}_2,+)$ has order 2; $E_1(\mathbb{Q}_2)$: quotient $\tilde{E}(\mathbb{F}_2)$ has order 4; $E_0(\mathbb{Q}_2)$: good reduction

We have $E_r(\mathbb{Q}_2) \cong (\mathbb{Z}_2,+)$ for $r > \frac{e}{p-1} = \frac{1}{2-1}$

$\therefore E_2(\mathbb{Q}_2)_{tors} \hookrightarrow \dfrac{E(\mathbb{Q}_2)}{E_2(\mathbb{Q}_2)}$ which has order 8.

(iv) Let $P \in E(\mathbb{Q})$
$\#\tilde{E}(\mathbb{F}_7)=7 \Rightarrow 7P \in E_1(\mathbb{Q}_7) \Rightarrow 7$ in denominator
$\#\tilde{E}(\mathbb{F}_5)=9 \Rightarrow 9P \in E_1(\mathbb{Q}_5) \Rightarrow 5$ in denominator.

2.

	Δ	$p=2$	3	5	7	11	13
(i)	$-26=-2.13$	—	3	9	9	6	—
(ii)	$-1664=-2^7.13$	—	7	7	7	14	—
(iii)	$2304=2^8.3^2$	—	—	8	8	8	16

(i) $E_1(\mathbb{Q}_3) \subset E(\mathbb{Q}_3)$ $\quad \therefore \#E(\mathbb{Q})_{tors} \leq 3$.
$\|\wr$ $\quad \uparrow$
$(\mathbb{Z}_3,+)$ quotient $\tilde{E}(\mathbb{F}_3) \cong \mathbb{Z}/3\mathbb{Z}$ (or use $p=3$ & $p=1$)

(ii) Taking $p=3$ & $p=5$ gives $\#E(\mathbb{Q})_{tors} \leq 7$

(iii) Taking $p=5$ & $p=7$ gives $\#E(\mathbb{Q})_{tors} \leq 8$

(i) $E(\mathbb{Q})_{tors} \cong \mathbb{Z}/3\mathbb{Z} = \{O,(0,0),(0,-1)\}$

(ii) $E(\mathbb{Q})_{tors} \cong \mathbb{Z}/7\mathbb{Z} = \{O,(0,0),(4,8),(2,4),(2,4),(4,0)(0$

(iii) $E(\mathbb{Q})_{tors} \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/4\mathbb{Z} = \{O,(0,0),(-1,0),(-4,0),(-2,\pm 2),(2,\pm 6,$

3.
$$\#\tilde{E}(\mathbb{F}_p) = 1 + \sum_{x \in \mathbb{F}_p} \left(1 + \left(\frac{x^3+\lambda x}{p}\right)\right)$$
$$= p+1-a_p$$

where
$$a_p = -\sum_{x \in \mathbb{F}_p^*} \left(\frac{x+\lambda x^{-1}}{p}\right)$$ (by Euler's criterion)
$$\equiv -\sum_{x \in \mathbb{F}_p^*} (x+\lambda x^{-1})^{2k} \pmod p$$ (by Lemma below)
$$\equiv \lambda^k \binom{2k}{k} \pmod p$$

Lemma Let $r \in \mathbb{Z}$. Then $\sum_{x \in \mathbb{F}_p^*} x^r = \begin{cases} -1 & \text{if } r \equiv 0 \pmod{p-1} \\ 0 & \text{if } r \not\equiv 0 \pmod{p-1} \end{cases}$

Proof Let $S = \sum_{x \in \mathbb{F}_p^*} x^r$. Let g be a primitive root mod p.

Replacing x by gx shows $S = g^r S$
If $r \not\equiv 0 \pmod{p-1}$ then $g^r \neq 1 \pmod p \Rightarrow S \equiv 0 \pmod p$
If $r \equiv 0 \pmod{p-1}$ then $S \equiv p-1 \equiv -1 \pmod p$ □

Since $p \neq 2$ and $\binom{2k}{k} = \frac{(2k)!}{(k!)^2}$ with $k < p$ it follows that $a_p \not\equiv 0 \pmod p$

If $p \equiv 3 \pmod 4$ then $\left(\frac{-1}{p}\right) = -1$. Since $f(x) = x^3 + ax$ is an odd function it follows that $a_p = 0$.

4 (i) Let $E : y^2 = x^3 + d$ $\quad m = \#E(\mathbb{Q})_{tors}$

If $p \nmid 6dm$ then $E(\mathbb{Q})_{tors} \hookrightarrow \tilde{E}(\mathbb{F}_p)$

If $p \equiv 2 \pmod 3$ then $\mathbb{F}_p^* \to \mathbb{F}_p^*$; $x \mapsto x^3$ an isomorphism

$$\begin{aligned} \#\tilde{E}(\mathbb{F}_p) &= 1 + \#\{(x,y) \in \mathbb{F}_p^2 \mid y^2 = x^3 + d\} \\ &= 1 + \#\{(x,y) \in \mathbb{F}_p^2 \mid y^2 = x + d\} \\ &= p + 1 \end{aligned}$$

$\therefore$ For all sufficiently large primes p with $p \equiv 2 \pmod 3$ we have $m \mid (p+1)$.

If $\ell \mid m$ for some prime $\ell \geq 5$, or $4 \mid m$ or $9 \mid m$ then this contradicts Dirichlet's Theorem on Primes in Arithmetic Progression.

$\therefore$ $m \mid 6$.

(ii) $E : y^2 = x^3 + 5$ $\qquad P = (-1, 2) \in E(\mathbb{Q})$

Clearly $E(\mathbb{Q})[2] = 0$.

By (i) it suffices to show $3P \neq 0$.

Either : $\quad 2P = \left(\left(\frac{3}{4}\right)^2 + 2, \ldots\right) \neq -P$

or : $\quad \#\tilde{E}(\mathbb{F}_7) = 7$

or : $\quad \Delta < 0 \Rightarrow E(\mathbb{R}) \cong \mathbb{R}/\mathbb{Z} \Rightarrow E(\mathbb{R})[3] = \{0, (0, \pm\sqrt{5})\}$

$\vdots$

5. Method (1) $\qquad$ Let $P = (x,y) \in E(\mathbb{Q})_{tors}$. Then $x, y \in \mathbb{Z}$

Equation for $E \Rightarrow y^2 = x(x^2 + ax + b)$ $\qquad (*)$

If $2P \neq 0$ then proof of Lutz-Nagell gives $\quad y \mid 3x^2 + 2ax + b \qquad (**)$

We claim that $x \mid b$

If not then there exists a prime p with $v_p(x) > v_p(b)$

$$(*) \Rightarrow \quad 2v_p(y) = v_p(x) + v_p(b)$$

$$(**) \Rightarrow \quad v_p(y) \leq v_p(b)$$

$$\therefore \quad v_p(x) + v_p(b) \leq 2v_p(b) \Rightarrow v_p(x) \leq v_p(b) \quad \not\!\!\not\!\!\not$$

If $2P = 0$, yet $x \neq 0$ then x is a root of $x^2 + ax + b = 0$ and so again $x \mid b$.

Finally $x \mid b \Rightarrow x + a + \frac{b}{x} = \left(\frac{y}{x}\right)^2 \in \mathbb{Z}$

$\Rightarrow x + a + b/x$ is a perfect square.

Method (2) $\qquad$ There is a 2-isogeny $\quad \phi : E \to E'$

$$(x,y) \mapsto \left(\left(\frac{y}{x}\right)^2, \frac{y(x^2-b)}{x^2}\right)$$

$$\begin{aligned} P = (x,y) \in E(\mathbb{Q})_{tors} &\Rightarrow \phi(P) \in E'(\mathbb{Q})_{tors} \\ &\Rightarrow \left(\frac{y}{x}\right)^2 \in \mathbb{Z} \\ &\Rightarrow x \mid b \text{ and } x + a + \frac{b}{x} \text{ is a perfect square.} \end{aligned}$$

6. (i) Take a minimal Weierstrass equation

$$y^2 + a_1xy + a_3y = x^3 + a_2x^2 + a_4x + a_6 \qquad a_i \in \mathbb{Z}_p$$

$$\begin{aligned} p \neq 2,3 &\Rightarrow \tfrac{1}{2}, \tfrac{1}{3} \in \mathbb{Z}_p \\ &\Rightarrow \text{the substitutions } y \leftarrow y - \tfrac{1}{2}a_1x - \tfrac{1}{2}a_3,\ x \leftarrow x - \tfrac{1}{3}a_2 \\ &\quad \text{preserve that } a_i \in \mathbb{Z}_p \ (\text{\& give } a_1 = a_2 = a_3 = 0) \end{aligned}$$

Since the discriminant is unchanged the equation is still minimal

(ii) Lemma $\quad y^2 = x^3 + ax + b$ is minimal $\iff$ $v_p(a) < 4$ or $v_p(b) < 6$

Proof "$\Rightarrow$" If $v_p(a) \geq 4$ and $v_p(b) \geq 6$ then

$y^2 = x^3 + p^{-4}ax + p^{-6}b$ is an integral (i.e. $\mathbb{Z}_p$-coefficient) Weierstrass equation with smaller valuation of the discriminant, contradicting minimality of the original equation.

"$\Leftarrow$" By (i) have minimal W. equation $y^2 = x^3 + Ax + B$

$a = u^4 A$, $b = u^6 B$ for some $u \in \mathbb{Q}_p^*$ $\quad \therefore\ 4a^3 + 27b^2 = u^{12}(4A^3 + 27B^2)$

$y^2 = x^3 + ax + b$ not minimal $\Rightarrow v_p(4a^3 + 27b^2) > v_p(4A^3 + 27B^2)$

$\Rightarrow v_p(u) > 0$

$\Rightarrow v_p(a) \geq 4$ and $v_p(b) \geq 6$ $\square$

(iii) $E/\mathbb{Q}_p$ has good reduction $\Leftrightarrow v_p(\Delta) = 0$

$E/\mathbb{Q}_p$ has multiplicative reduction

$\Leftrightarrow v_p(\Delta) > 0$ & $v_p(a) = v_p(b) = 0$

$E/\mathbb{Q}_p$ has additive reduction $\Leftrightarrow v_p(a) > 0$ & $v_p(b) > 0$

Indeed for additive reduction $x^3 + ax + b \equiv (x - \alpha)^3 \pmod p$

$\Rightarrow p \mid a$ and $p \mid b$

(Also note that if $p \mid \Delta$ then $p \mid a \Leftrightarrow p \mid b$)

$E/\mathbb{Q}_p$ has good reduction $\Rightarrow v_p(\Delta) = 0 \Rightarrow v_K(\Delta) = 0$

$\therefore$ Weierstrass equation still minimal over K

$\therefore$ E/K has good reduction.

$E/\mathbb{Q}_p$ has ~~additive~~ multiplicative reduction $\Rightarrow v_p(\Delta) > 0$ & $v_p(a) = 0$

$\Rightarrow v_K(\Delta) > 0$ & $v_K(a) = 0$

$\therefore$ Weierstrass equation still minimal over K

$\therefore$ E/K has multiplicative reduction

Let E: $y^2 = x^3 + p$ $\qquad K = \mathbb{Q}_p(\sqrt[6]{p})$

Then $E/\mathbb{Q}_p$ has additive reduction, yet E/K has good reduction.

7. $y^2 = x^2(x+1)$.

Putting $y = ux$ gave parametrisation $(x, y) = (u^2 - 1, u(u^2 - 1))$

$u = \pm 1 \iff$ singular point $\iff t = 0, \infty$

$u = \infty \iff$ point at $\infty \iff t = 1$

This suggests putting $t = \frac{u-1}{u+1}$, ie. $u = \frac{1+t}{1-t}$

$$\phi(t) = \left(\frac{1+t}{1-t}\right)^2 - 1 = \frac{4t}{(1-t)^2}$$

$$\psi(t) = \frac{1+t}{1-t}\,\phi(t) = \frac{4t(t+1)}{(1-t)^3}$$

There is a bijection $E_{ns}(K) \longleftrightarrow K^*$

$(x, y) \longmapsto \frac{y-x}{y+x}$

$(\phi(t), \psi(t)) \longleftarrow\!\shortmid\ t$

To show this is a group homomorphism, consider

$P_1, P_2, P_3 \in E_{ns}(K)$ with $P_1 + P_2 + P_3 = 0$, $\quad P_1, P_2, P_3 \neq O$

Write $P_i = (\phi(t_i), \psi(t_i))$

P_1, P_2, P_3 are collinear, say lying on the line $ax + by = 1$

Then t_1, t_2, t_3 are the roots of

$$4a\,t(1-t) + 4b\,t(t+1) = (1-t)^3$$

Coefficients of t^3 and t^0 $\Rightarrow$ $t_1 t_2 t_3 = 1$

8. We have 2-isogenous elliptic curves

E: $y^2 = x(x^2 + ax + b)$

E': $y^2 = x(x^2 + a'x + b')$ $\qquad a' = -2a,\ b' = a^2 - 4b$

Taking $a = u$, $b = -16$ gives $a' = -2u$, $b' = u^2 + 64 = p$

Moreover $\Delta(E) = 16\,b^2(a^2 - 4b) = 2^{12} p$

$\Delta(E') = 16\,p^2(4u^2 - 4p) = -2^{12} p^2$

To show E has good reduction at 2

E: $(y + x)^2 = x^3 + ux^2 - 16x$

$\rightsquigarrow$ $y^2 + 2xy = x^3 + (u-1)x^2 - 16x$

$\rightsquigarrow$ $y^2 + xy = x^3 + \frac{u-1}{4}x^2 - x$ $\qquad (\Delta = p)$

To show E' has good reduction at 2

$$E': \quad y^2 = x\left((x-u)^2+64\right)$$
$$\rightsquigarrow \quad (y+x)^2 = (x+u)(x^2+64)$$
$$\rightsquigarrow \quad y^2+2xy = x^3+(u-1)x^2+64x+64u$$
$$\rightsquigarrow \quad y^2+xy = x^3+\frac{u-1}{4}x^2+4x+u \qquad (\Delta = -p^2)$$

Tamagawa numbers at p?

$$E: \quad y^2 = x\left((x+\tfrac{1}{2}u)^2-\tfrac{1}{4}p\right)$$

If $(x,y) \in E(\mathbb{Q}_p)$ reduces to the singular point then
$v_p(x+\frac{1}{2}u) \geq 1$ & $v_p(y) \geq 1 \implies v_p(\frac{1}{4}p) \geq 2$ ✗
$\therefore c_p(E) = 1$

On E' the point $T=(0,0)$ reduces to the singular point
$\therefore c_p(E') > 1$

(If $P=(x,y) \in E'(\mathbb{Q}_p)$ then $P+T = (\frac{p}{x}, \dots)$
$\therefore$ exactly one out of P and $P+T$ reduces to the singular point $\therefore c_p(E')=2$)

9 (i) Consider the morphism $\psi: E \to E$; $P \mapsto \phi(P)-P$
If ψ is surjective then ϕ has a fixed point.
Otherwise ψ is constant, so ϕ (& hence ϕ^n) is a translation map.

(ii) Say $C \subset \mathbb{P}^d$. Let $\phi: C \to C$, $(x_0 : \dots : x_d) \mapsto (x_0^q : \dots : x_d^q)$ — Frobenius
We have $C(\mathbb{F}_{q^n}) = \{P \in C \mid \phi^n(P) = P\}$

Picking $P \in C(\overline{\mathbb{F}}_q)$ gives an elliptic curve (E,P) over $\overline{\mathbb{F}}_q$
If $P=(a_0 : \dots : a_d)$, $a_i \in \overline{\mathbb{F}}_q$ then $[\mathbb{F}_q(a_0,\dots,a_d) : \mathbb{F}_q] < \infty$
So $\exists\, n \geq 1$ s.t. $0 < |C(\mathbb{F}_{q^n})| < \infty$
$\implies \phi^n$ cannot be a translation map
$\implies \phi$ cannot be a translation map
$\implies C(\mathbb{F}_q) \neq \emptyset$ by (i)

10. $E/\mathbb{Q}_p \quad y^2 = x^3+ax+b \quad a,b \in \mathbb{Z}_p \quad p \geq 5$

(i) Taking $a=-3$, $b=2+p^n$ gives a minimal W. equation with $4a^3+27b^2 = 27(4p^n+p^{2n}) \implies v_p(\Delta) = n$

(ii) If $E/\mathbb{Q}_p$ has additive reduction then
$x^3+ax+b \equiv (x-\alpha)^3 \pmod p$ for some $\alpha \in \mathbb{Z}_p$
Coefficient of $x^2 \implies \alpha \equiv 0 \pmod p \implies p \mid a$ and $p \mid b$
If $v_p(\Delta_E) \geq 12$ then $p^{12} \mid (4a^3+27b^2)$
Then $p^3 \mid b^2 \implies p^2 \mid b$
& $p^4 \mid a^3 \implies p^2 \mid a$
& $p^5 \mid b^2 \implies p^3 \mid b$

Let $E': y^2 = x^3 + p^{-2}a\,x + p^{-3}b$] quadratic twist of E by p
If $E'/\mathbb{Q}_p$ has additive reduction then repeating the above argument gives $p^4 \mid a$ and $p^6 \mid b$. This contradicts that we started with a minimal Weierstrass equation.
Therefore at least one out of E and E' has multiplicative red^n.

11. Let $C = B/A$. Applying the snake lemma to the diagram

$$\begin{array}{ccccccccc} 0 & \to & A & \to & B & \to & C & \to & 0 \\ & & \downarrow{\scriptstyle \times n} & & \downarrow{\scriptstyle \times n} & & \downarrow{\scriptstyle \times n} & & \\ 0 & \to & A & \to & B & \to & C & \to & 0 \end{array}$$

gives an exact sequence

$$0 \to A[n] \to B[n] \to C[n] \to \frac{A}{nA} \to \frac{B}{nB} \to \frac{C}{nC} \to 0$$

$$\implies q(B) = q(A)\,q(C)$$

The exact sequence $0 \to C[n] \to C \xrightarrow{\times n} C \to \frac{C}{nC} \to 0$
shows that if C is finite then $q(C)=1$
$\therefore q(A) = q(B)$

12. **Lemma** $\mathcal{O}_K^*$ and $E(K)$ have subgroups of finite index isomorphic to $(\mathcal{O}_K, +)$

Proof

$$\begin{array}{ccccccc} \hat{E}_m(\pi^r\mathcal{O}_K) & & & & \hat{E}_m(\pi\mathcal{O}_K) & & \\ \| & & & & \| & & \\ 1+\pi^r\mathcal{O}_K & \subset & \cdots & \subset & 1+\pi\mathcal{O}_K & \subset & \mathcal{O}_K^* \\ \text{if } r > \frac{e}{p-1} \longrightarrow \| & & & & & & \\ (\mathcal{O}_K, +) & & \text{quotients} \cong (k,+) & & & & \text{quotient} \cong k^* \end{array}$$

For $E(K)$ the result was proved in lectures $\square$

By Question 11

$$\frac{|\mathcal{O}_K^*/(\mathcal{O}_K^*)^n|}{|\mu_n(K)|} = \frac{|\mathcal{O}_K/n\mathcal{O}_K|}{1}$$

$$\frac{|E(K)/nE(K)|}{|E(K)[n]|} = \frac{|\mathcal{O}_K/n\mathcal{O}_K|}{1}$$