Torsion points on modular curves and Galois Theory

Kenneth A. Ribet and Minhyong Kim

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In elementary terms, the arithmetic theory of a curve X is concerned with solutions to a geometrically irreducible polynomial equation in two variables:

$$f(x, y) = 0 \qquad (*)$$

In contrast to the geometric theory, where the different kinds of number pairs (x, y) that can occur as solutions are viewed as homogeneous, the arithmetic b g gggj b b bbstudy classifies more carefully the structure of solutions of specific type. That is, one tries to understand the solutions to the equation (*) where (x, y) are constrained to lie in some arithmetically defined set. One common case is that of rational solutions or, more generally, the case of solutions where x, y are constrained to lie inside a fixed number field F. For example, when $f(x, y)$ has genus 1 (that is, the smooth points of the complex solution set form a genus one Riemann surface with punctures), the Mordell-Weil theorem says the solution set, in conjunction with a few additional points, acquires the natural structure of a finitely generated abelian group. For another example, when the genus is greater than one, Faltings [8] proved that the solution set is finite. In both cases, one derives finite-type structures for the solution set from finiteness contraints on the 'type' of the solution. A theorem of Ihara-Serre-Tate [11] gives an example of finiteness theorems deriving from a different kind of arithmetic constraint. Namely, one considers solutions that are roots of unity of arbitrary order. Then as soon as the genus is at least one, there are again only finitely many solutions to (*). It is interesting to note that in this case, the constraint in question is of 'group-type' in contrast to the 'field-type' constraint of the other two examples.

A conjecture of Manin and Mumford as proved by Raynaud [17] deals with the projective case of this theorem. What is meant by the projective case? In the Ihara-Serre-Tate theorem, one can view the curve X as essentially lying in the affine torus $\mathbf{C}^* \times \mathbf{C}^*$ and the assertion is that X has a finite intersection with the torsion points of the torus. Now, when X is a projective smooth curve of genus at least two, it has an essentially canonical embedding into a group variety $J = J(X)$, the Jacobian of X. Raynaud's theorem states that the intersection between X and J_{tor}, the torsion subgroup of J, is finite. It should also be noted that Raynaud generalizes this statement considerably to include refined statements about intersections between subvarieties of abelian varieties and division points of finitely generated groups [18], while a common generalization of the projective and affine case concerned with subvarieties of semi-abelian varieties has been found by Hindry [10].

On the other hand, Coleman [2] [3] [4] has stressed the importance of actually being able to determine explicitly the finite set occuring in Raynaud theorem for specific curves. In fact, unlike the case of Faltings' theorem there has been some recent success in making Raynaud's theorem completely effective, most notably in the case of Fermat curves, due to Coleman, Tamagawa, and Tzermias [6], and the modular curves $X_0(N)$ for N prime, due to Baker [1] and Tamagawa. A new proof for the modular curve case was given by Ken Ribet using a refined analysis of the Eisenstein torsion in $J_0(N)$ and this paper is devoted to an exposition of this proof. It is similar in many ways to the second proof of [1] except for conceptual simplifications arising from systematic use of the notion of an 'almost rational torsion point.' In particular, a complete computation of these points is given for $J_0(N)$, N prime and Lemma 1 makes clear how the main theorem hinges upon this notion. The result in question was first conjectured by Coleman, Kaskel, and Ribet [5] and we go on to describe the statement. As mentioned, we will always be interested in N prime, and $N \geq 23$ (which occurs iff $X_0(N)$ has genus ≥ 2). $X_0(N)$ has two cusps corresponding to the orbits of 0 and ∞ in the extended upper half-plane, and we will use the latter, again denoted ∞ to embed $X_0(N)$ into its Jacobian $i : X_0(N) \hookrightarrow J_0(N)$. That is, a point $P \in X_0(N)$ maps to the class of the divisor $[P] - [\infty]$. In the following, we will suppress the embedding i from the notation or leave it in according to convenience. By a theorem of Manin and Drinfeld [7], the other cusp point 0 is a torsion point under this embedding. Another way for a torsion point to arise is as follows: the curve $X_0(N)$ has an involution w which switches 0 and ∞, that is, $0 = w(\infty)$. Denote by $X_0(N)^+$ the curve obtained as the quotient of $X_0(N)$ by the action of this involution. Now, it can happen that $X_0(N)^+$ is a curve of genus zero, in which case $X_0(N)$ is a hyperelliptic curve. Let

$$f : X_0(N) \rightarrow X_0(N)^+$$

be the quotient map and let $P \in X$ be a Weierstrass point. The inverse image divisor of any two points are rationally equivalent, since $X_0(N)^+ \simeq \mathbb{P}^1$. In particular, $2[P] = [\infty] + [0]$. Thus, $2i(P) = i(0)$ and $i(P)$ is a torsion point. According to Ogg [16], the values of N for which $X_0(N)$ is hyperelliptic are $23, 29, 31, 37, 41, 47, 59, 71$. In the case of $N = 37$ the hyperelliptic involution h is different from w. That is $X_0(37)$ is hyperelliptic even though $X(37)^+$ is not of genus zero. It was shown by Mazur and Swinnerton-dyer [15] that in this case $[\infty] - [h(\infty)]$ is of infinite order in $J_0(37)$. From this it is an easy exercise to deduce that the Weierstrass points are not torsion in this case. That is, hyperelliptic torsion points occur only when $X_0(N)^+$ is of genus zero. Thus, we will have completely determined the torsion points as soon as we have found the non-Weierstrass ones.

The conjecture of Coleman, Kaskel, and Ribet as proved by Baker and Tamagawa says, in fact,

Theorem 1 *(Baker, Tamagawa)* $[X_0(N) - (\textit{Weierstrass points})] \cap J_{tor} = \{0, \infty\}$.

1 Almost rational torsion points

Lang's original suggestion [12] was to prove the Manin-Mumford conjecture itself using Galois theory. Let's suppose given a curve C embedded in an abelian variety A. The data is defined over some field K finitely generated over the rationals, and hence, the torsion points of A will admit an action of the Galois group $G = \mathrm{Gal}(\overline{K}/K)$. This action induces a representation

$$\rho : G \to \mathrm{Aut}(\hat{T}A)$$

where $\hat{T}A$ denotes the adelic Tate module of A. Lang's conjecture concerned the intersection between the image $\rho(G)$ of G and the group of homotheties $\hat{\mathbf{Z}}^* \subset \mathrm{Aut}(\hat{T}A)$. He conjectured that $\rho(G) \cap \hat{\mathbf{Z}}^*$ is of finite index in $\hat{\mathbf{Z}}$. The Manin-Mumford conjecture follows from this by an elementary argument.

Although Lang's conjecture is still unproven, Serre proved a weaker version in his College de France lectures 85-86 [21]. That is, he proved that $\hat{\mathbf{Z}}^*/\rho(G) \cap \hat{\mathbf{Z}}^*$ is of finite exponent. Using Serre's result Ribet manages to give a very elegant proof of the Manin-Mumford conjecture.

In this proof crucial use is made of the notion of an 'almost rational' torsion points, which we will abbreviate to a.r.t.:

Definition 1 *Let A be an abelian variety over a field k. A point $p \in A(\bar{k})$ is called almost rational (a.r.) if*

$$\sigma(p) - p = p - \tau(p) \Rightarrow p = \sigma(p) = \tau(p)$$

for all $\sigma, \tau \in Gal(\bar{k}/k)$.

Here are a few elementary facts that follow directly from the definition:

-Rational points are almost rational.

-A Galois conjugate of an a.r. point is a.r.

-If P is almost rational and $2\sigma(P) - 2P = 0$ then $\sigma(P) = P$.

The definition is not likely to be very intuitive, so it is probably best to see right away a concrete result that uses it.

Lemma 1 *Let X be a curve of genus at least 2 embedded in its Jacobian J via a rational point p_0. Then*

$$X = X_{a.r.} \cup (\textit{Weierstrass points})$$

Thus, we get an inclusion $X_{tor} - (\text{w.p.}) \subset J_{a.r.t.}$ reducing the Baker-Tamagawa theorem to a study of $J_{a.r.t.}$.

Proof of Lemma. Suppose $[P] - [P_0]$ is not almost rational. Then there are σ and τ in the Galois group such that $[\sigma(P)] - [P] \sim [P] - [\tau(P)]$ as divisors and neither are equivalent to zero. Thus, $2[P] - [\sigma(P)] - [\tau(P)] \sim 0$, meaning we can find a rational function with a pole of order two at P. That is, P is a Weierstrass point.

We will investigate this notion extensively in the specific context of modular curves in order to prove the Baker-Tamagawa theorem. In the meanwhile, we outline how to deduce the Manin-Mumford conjecture from Serre's result. In fact, Manin-Mumford follows in an obvious way from Lemma 1 and the following theorem, whose proof will occupy us to the end of this section.

Theorem 2 *Let A be an abelian variety over a finitely generated field k. Then $A_{a.r.t}$ is finite.*

In the course of the proof, we will need the following simple

Lemma 2 *For each $e \geq 1$, we can find $C(e) > 0$ such that for any $m > C(e)$, there exist $x, y \in (\mathbf{Z}/m\mathbf{Z})^*)^e$ with $x \neq 1, y \neq 1$ and $x + y = 2$.*

Proof. First note that if $m = \prod p^{n_p}$, then by the Chinese remainder theorem, one need prove the existence of x, y for just one of the $\mathbf{Z}/p^{n_p}\mathbf{Z}$ and set the modulus for the other factors to be 1. Also, by setting $C(e)$ sufficiently large, we can make sure that there is at least one prime power factor $p^n \geq A(e)$, where $A(e)$ is the maximum of e^3 and the smallest prime l such that $x^e + y^e = 2$ has at least $e^2 + 2e + 1$ solutions in $\mathbf{F}_l$. Such an l clearly exists by elementary counting when e is 1 or 2 and by the Weil bounds when $e \geq 3$.

In the case $n \geq 2$ write $e = up^k$ where u is relatively prime to p. Now put $x = 1 + ep^{n-k-1}$ and $y = 1 - ep^{n-k-1}$ and note that $p^n \geq e^3 = u^3p^{3k}$ implies that $k \leq \lfloor n/3 \rfloor \leq n - 2$ so that x and y are both units in $\mathbf{Z}/p^n$. Clearly $x, y \neq 1 \pmod{p^n}$ but $x + y = 2 \pmod{p^n}$. It is also easily checked that $x = (1 + p^{n-k-1})^e$ and $y = (1 - p^{n-k-1})^e \pmod{p^n}$. Next suppose $n = 1$. Then we are looking for solutions to $x^e + y^e = 2$ in $\mathbf{F}_p$ such that neither x^e nor y^e are 0 or 1. We are done by counting number of points mod p.

It is easy to sharpen the proof slightly and take $C(e) = 3$ if $e = 1$.

Proof of theorem. According to Serre, if we consider the action $\rho : G \rightarrow \mathrm{Aut}(\hat{T}A)$ of the Galois group on the adelic Tate module, $\hat{\mathbf{Z}}^*/\rho(G) \cap \hat{\mathbf{Z}}^*$ has finite exponent e. We claim that if P is a torsion point of order $m > C(e)$, the P is not a.r. To see this, let $x, y \in ((\mathbf{Z}/m\mathbf{Z})^*)^e$ satisfy the conditions of the proposition. Find $\sigma, \tau \in G$ such that $\sigma \mapsto x$ and $\tau \mapsto y$ as operators on $A[m]$. Then we have

$$\sigma(P) + \tau(P) = 2P \Rightarrow \sigma(P) - P = P - \tau(P)$$

but $\sigma(P) - P = (x-1)P \neq 0$. That is, P is not almost rational.

Thus, the general finiteness follows from very general considerations. To prove the target theorem in the case of modular curves, we will end up needing a very precise understanding of the a.r.t. points for modular Jacobians, in particular, their relation to other canonically defined subgroups together with their Galois-theoretic properties. We will review the relevant facts in the next section.

We close this section with a few lemmas for use in the proof of the main theorem.

Lemma 3 *Let $A/\mathbf{Q}$ be an abelian variety and suppose $P \in A[n]$, $n > 3$, is a cyclotomic point: $\sigma(P) = \chi_n(\sigma)P$ for all $\sigma \in Gal(\overline{\mathbf{Q}}/\mathbf{Q})$, where χ_n is the mod n cyclotomic character. Then P is not a.r.*

Proof. As noted above, it is easy to see that if $n > 3$, then there exist $s, t \in (\mathbf{Z}/n\mathbf{Z})^*$ such that $s \neq 1, t \neq 1$ and $s + t = 2$. Find σ, τ such that $\chi_n(\sigma) = s$ and $\chi_n(\tau) = t$. Then $\sigma(P) + \tau(P) = 2P$ but $\sigma(P) - P = sP - P \neq 0$. So P is not a.r.

Lemma 4 *Let A/k, k a number field. Let v be prime of k and assume A has semi-stable reduction at v. Let $P \in A_{a.r.t}$ have order prime to v. Then $k(P)$ is unramified at v.*

Proof. Let $\sigma \in I_v$, the inertia group at v. According to Grothendieck ([9], see also following section), the action of I_v on prime to v torsion is two-step unipotent. So

$$\begin{aligned} (\sigma - 1)^2 P = 0 \quad &\Rightarrow \quad \sigma^2 P - 2\sigma P + P = 0 \\ &\Rightarrow \quad \sigma P + \sigma^{-1} P = 2P \\ &\Rightarrow \quad \sigma(P) = P \end{aligned}$$

the last implication following from the assumption that P is a.r. Therefore, I_v acts trivially on P.

2 Background on Modular curves

In this section, we summarize the facts we need from the theory of modular curves, especially results about the Galois representations associated to their Jacobians. (See [13] and references therein for a general overview.)

Recall that the modular curve $X_0(N)$ is the projective smooth model of the modular curve $Y_0(N)$ which parametrizes pairs (E, C) where E is an elliptic curve and C is a cyclic subgroup of order N. $Y_0(N)$ and $X_0(N)$ are defined over $\mathbf{Q}$, and over the complex numbers, we have

$$Y_0(N)(\mathbf{C}) = H/\Gamma_0(N)$$

while

$$X_0(N)(\mathbf{C}) = [H \cup \mathbb{P}^1(\mathbf{Q})]/\Gamma_0(N)$$

When N is prime, which is the case that will concern us, $\Gamma_0(N)$ has two orbits on $\mathbb{P}^1(\mathbf{Q})$, the orbits of 0 and ∞. We will denote by the same symbols the corresponding points on $X_0(N)$. We denote by $J_0(N)$ the Jacobian of $X_0(N)$, which parametrizes divisor classes of degree zero on $X_0(N)$. The Abel-Jacobi embedding $X_0(N) \hookrightarrow J_0(N)$ with respect to the point ∞ is described at the level of points by sending a point P to the class of the divisor $[P] - [\infty]$. We will use this to identify $X_0(N)$ with its image and think of it as a subvariety of $J_0(N)$. The Manin-Drinfeld theorem says that $[0] - [\infty]$ generates a finite subgroup C

of $J_0(N)$ which we call the *cuspidal subgroup*. We will denote by n the order of C which is equal to the denominator of $(N-1)/12$ ([13] p. 99).

Another important subgroup is the Shimura subgroup Σ of $J_0(N)$ defined as follows. There is a map $X_1(N) \rightarrow X_0(N)$ of degree $\phi(N) = N-1$ from the compactification $X_1(N)$ of the modular curve $Y_1(N)$ which parametrizes pairs (E, P), where E is an elliptic curve and P is a point of order N. On the points of $Y_1(N)$ this map simply takes (E, P) to $(E, < P >)$, $< P >$ being the subgroup generated by P. This gives rise to a map $X_2(N) \rightarrow X_0(N)$ which is the maximal étale intermediate covering to $X_1(N) \rightarrow X_0(N)$. Thus we get a map $J_2(N) \rightarrow J_0(N)$, where $J_2(N)$ is the Jacobian of $X_2(N)$. Σ is simply the kernel of the dual map. Thus, the points of Σ correspond to line bundles of degree zero on $X_0(N)$ which become trivial when pulled back to $X_2(N)$. It has order n and is isomorphic to μ_n as a Galois module ([13] p.99).

The modular Jacobians admit an action of the algebra $\mathbf{T}$ of Hecke operators ([13], section II.6). This is the $\mathbf{Z}-$algebra of endomorphisms generated by the correspondences T_l for each prime $l \neq N$ and the Atkin-Lehner involution w_N. They are defined on points of $Y_0(N)$ by the formula

$$T_l : (E, C) \mapsto \Sigma_{C'}(E/C', (C + C')/C')$$

where C' runs over the cyclic subgroups of E of order l and

$$w_N : (E, C) \mapsto (E/C, E[N]/C).$$

The Eisenstein ideal I of $\mathbf{T}$ is the ideal generated by $T_l - (l + 1)$ for $l \neq N$ and $1 + w_N$ ([13] p.95). Of particular importance will be the structure of the subgroup $J_0(N)[I] \subset J_0(N)$ annihilated by I.

We now list the main difficult facts we will use:

0. $\mathbf{T}/I \simeq \mathbf{Z}/n$ ([13], Prop. 9.7). So if a maximal ideal m is 'Eisenstein', i.e., contains I, then $\mathbf{T}/m$ has characteristic l dividing n.

1. $J_0(N)[I] = C \oplus \Sigma$ if n is odd while $J_0(N)[I]$ contains $C + \Sigma$ as a subgroup of index two and $C \cap \Sigma = C[2] = \Sigma[2]$ if n is even. This follows from the fact that $C + \Sigma$ are contained in $J_0(N)[I]$ and that $J_0(N)[I]$ is free of rank two over $\mathbf{T}/I$. (See [13], sections II.16-18, and Prop. II.11.11 together with the explanation in [20], section 3.)

2. We will need some detailed facts about the action of the Galois group $\mathrm{Gal}(\bar{Q}/Q)$ on the torsion points of $J_0(N)$. One analyzes these representations by breaking them up into simple $\mathbf{T}[G]$-modules. Such simple modules are associated to maximal ideals m inside the Hecke algebra $\mathbf{T}$. In fact, for each m there is a two-dimensional semi-simple representation, unique up to isomorphism,

$$\rho_m : G \rightarrow GL_2(\mathbf{T}/m)$$

characterized by the properties (citeRi1, section 5):

-ρ_m is unramified outside N and l, where $l = m \cap \mathbf{Z}$.

For $p \neq N, l$, the Frobenii Fr_p satisfy

-Tr$(\rho_m(Fr_p)) = T_p \pmod{m}$
-and $\det(\rho_m(Fr_p)) = p$
Furthermore, one knows that ρ_m is irreducible if m is non-Eisenstein, i.e., when m does not contain the Eisenstein ideal I, and if $I \subset m$, then ρ_m is $\mathbf{Z}/l \oplus \mu_l$ ([13] Prop. 14.1 and 14.2).

3. Concerning the action of I_N, the inertia group at N, on the torsion of $J_0(N)$, one has Grothendieck's exact sequence ([9] 11.6 and 11.7)

$$0 \to \mathrm{Hom}(X, \mu_r) \to J_0(N)[r] \to X/rX \to 0$$

for any r, where X is the character group of the toral part of the reduction of $J_0(N)$ mod N. This implies, for example, that the action is 2-step unipotent if r is prime to N. One notes also that even when $N|r$, the first and last terms are finite, in that they extend to finite flat group schemes over $\mathbf{Z}_N$.

4. On the other hand, a theorem of Ribet ([20] Prop. 2.2) addresses fine behaviour of ρ_m at N for m non-Eisenstein. It says that ρ_m is not finite at N if $m|N$ and that it is ramified at N if m is prime to N. This is an instance of the 'level-lowering' theorem [19] together with a result of Tate on mod 2 representations unramified outside 2 [22].
For $m|N$, ρ_m occurs in $J_0(N)[N]$, so as an I_N module, it fits into an exact sequence

$$0 \to \mu_N \to \rho_m \to \mathbf{Z}/N \to 0$$

which is non-split, since the existence of a splitting would imply finiteness for ρ_m. So we draw the conclusion that $\rho_m(I_N)$ is non-abelian in this case, a fact which will turn out to be very important in the proof of the Baker-Tamagawa theorem.

5. A theorem of Ribet says that $J_0(N)[I]$ is exactly the set of torsion in $J_0(N)$ that is unramified at N. ([20] Prop. 3.1, 3.2) That $J_0(N)[I]$ is unramified at N for n odd follows obviously from $J_0(N)[I] = C \oplus \Sigma$. When n is even, one still gets an isomorphism

$$J_0(N)[I] = \mathrm{Hom}(X/IX, \mu_n) \oplus \Sigma$$

: The two groups on right hand side inject into the left by 1 and 3 and the images do not intersect [13], (Prop. II.11.9). But they also have the same order by 1. and an argument of [20], theorem 2.3, showing that X/IX is cyclic.
To go the other way, given an unramified torsion point $P \in J_0(N)$, one uses 4. to conclude that the simple constituents of the module $M := \mathbf{T}[G]P + J_0(N)[I]$ all come from Eisenstein primes, and therefore, are of the form $\mathbf{Z}/l$ or μ_l for $l|n$. So the constituents are all annihilated by I. In fact, it is easy to see that M itself is of the form

$$0 \to S \to M \to Q \to 0$$

where Q is constant and S is of μ-type. But Σ is the maximal μ-type group in $J_0(N)$ ([13], theorem 2) so $S = \Sigma$. Now, reduction mod N and the isomorphism between Σ and the component group of $J_0(N)$ mod N gives us a splitting of this exact sequence. So one need only show that I annihilates Q. The Eichler-Shimura relation say that

$$T_l \cong Fr_l + lFr_l^t$$

(mod l, $l \neq N$), and therefore, the constant group Q is annihilated by $\eta_l = T_l - (1+l)$ for $l \neq N, (l,n) = 1$. (The order of Q divides some power of n, so reduction mod l is injective on Q for l prime to n.)

To show that it is also annihilated by all of I, we decompose into m-primary factors for Eisenstein primes m (which is possible since Q is annihilated by some power of I) and then show that each factor is annihilated using local principality of the Eisenstein ideal ([13], theorem II.18.10).

6.According to a theorem of Ribet ([20] Theorem I.7), the field $k(J_0(N)[I])$ generated by the Eisenstein torsion is $\mathbf{Q}(\mu_{2n})$ while $k(C,\Sigma) = \mathbf{Q}(\mu_n)$ according to the above-mentioned structure of C and Σ. The proof of the first fact follows from a careful study of $J_0(N)[I]$, but appears a bit too elaborate to summarize in a few words. Nevertheless, note that for n odd, the first fact follows easily from the second.

7. Finally, it is explained by Coleman-Kaskel-Ribet [5] that Mazur's theorems imply the useful fact that $X_0(N) \cap C = \{0, \infty\}$. For most N, that is, $N \neq 37, 43, 67, 163$, it is an obvious consequence of the fact that the cusps are the only rational points of $X_0(N)$. The remaining cases can be treated by more elementary arguments.

3 The theorem of Baker-Tamagawa

The main result which provides the key is the following

Theorem 3 $J_0(N)_{a.r.t} = C \oplus \Sigma[3]$

This detailed knowledge is what makes it possible to determine the torsion points on $X_0(N)$ so explicitly.

Let us first show how the theorem implies the theorem of Baker and Tamagawa.

This implication divides into two cases. Recall the curve $X_0(N)^+$ obtained as the quotient of $X_0(N)$ by the action of w, the Atkin-Lehner involution. The first case is when $X_0(N)^+$ has positive genus. Then the projection

$$f : X_0(N) \rightarrow X_0(N)^+$$

induces a commutative diagram:

$$\begin{array}{ccc} X_0(N) & \hookrightarrow & J_0(N) \\ \downarrow & & \downarrow \\ X_0(N)^+ & \hookrightarrow & J_0(N)^+ \end{array}$$

where $J_0(N)^+$ denotes the Jacobian of $X_0(N)^+$. According to the theorem,

$$J_0(N)_{a.r.t.} \subset J_0(N)[I] \subset J_0(N)[1+w]$$

Now, if D is a degree zero divisor on $X_0(N)$, then

$$D + wD = f^* f_*(D).$$

So if $D + wD \sim 0$, then the class of $f_*(D)$ is in the kernel of

$$f^* : J_0(N)^+ \to J_0(N).$$

But since w has a fixed point, this map is injective. Thus,

$$J_0(N)[1+w] \to 0 \in J_0(N)^+,$$

and therefore,

$$J_0(N)_{a.r.t} \to 0.$$

But this implies that

$$X_0(N)_{tor} \to \infty \in X_0(N)^+$$

and hence that $X_0(N)_{tor} = \{0, \infty\}$ as desired.

The second case is when $X_0(N)^+$ fails to have positive genus, that is, when $N = 23, 29, 31, 41, 47, 59, 71$. In this case, N is not congruent to 1 mod 9 which in turn implies that 3 does not divide n. Therefore, by theorem 2 $J_0(N)_{a.r.t.} = C$, and we get

$$X_0(N)_{tor} \subset X_0(N) \cap C = \{0, \infty\}$$

again.

So it remains to prove the structure theorem for $J_0(N)_{a.r.t.}$.

We wish to show first that $J_0(N)_{a.r.t.} \subset J_0(N)[I]$, which is the hard part of the proof. This is achieved by proving that the points in $J_0(N)_{a.r.t.}$ are unramified at N, and using Ribet's theorem identifying such points with $J_0(N)[I]$.

To prove that $J_0(N)_{a.r.t}$ consists of points unramified over N it suffices to show that the points have order prime to N (Lemma 4). So let $P \in J_0(N)_{a.r.t.}$ and analyze the module $M := \mathbf{T}[G]P$ by breaking it into its simple constituents, the possibilities for which we described in the previous section. Let r be the order of P. Thus, we have $M \subset J_0(N)[r]$.

In order to see that $J_0(N)_{a.r.t} \subset J_0(N)[I]$, recall from the previous section that as an I_N module, $J_0(N)[r]$ fits into an exact sequence

$$0 \to \mathrm{Hom}(X, \mu_r) \to J_0(N)[r] \to X/rX \to 0$$

Therefore

$$I'_N := \mathrm{Ker}(\chi_r : I_N \to (\mathbf{Z}/r)^*)$$

acts on $J_0(N)[r]$ by two-step unipotent transformations. But this implies by the argument of lemma 4 that $\sigma(P) = P$ for all $\sigma \in I'_N$. The same argument also applies to the conjugates of P since they are also a.r.t. Therefore, I'_N acts trivially on M. That is, I_N acts through the quotient $I_N/I'_N \hookrightarrow (\mathbf{Z}/r)^*$ on M and all its constituents. From this, we see that ρ_m for $m|N$ is ruled out as a simple factor (since $\rho_m(I_N)$ is non-abelian in that case) leaving $\mathbf{Z}/l$, μ_l, and

ρ_m, for m not dividing N as possibilities. Since the one-dimensional factors only occur in the Eisenstein case, we get $l|n$ and therefore, l is relatively prime to N. We conclude that M must have order prime to N, and hence, so must P. Therefore, $P \in J_0(N)[I]$ as desired.

In fact, we claim that $P \in \Sigma + C$. For if $P \notin \Sigma + C$ (which occurs only when n is even), P must generate $J_0(N)[I]/(\Sigma + C)$, so by the result of Csirik, we must have $\mathbf{Q}(P, \Sigma, C) = \mathbf{Q}(\mu_{2n})$. Also, $\mathbf{Q}(\Sigma, C) = \mathbf{Q}(\mu_n)$. Therefore, we can find $\sigma \in G$ such that $\sigma(P) - P \neq 0$ and σ acts trivially on $C + \Sigma$. But we have $2P \in \Sigma + C$, so that $\sigma(2P) - 2P = 0$. This contradicts the assumption that P is a.r. by our remark following the definition of a.r.

So we have $P \in \Sigma + C$ and we can write $P = Q + R$ for $Q \in \Sigma$ and $R \in C$. Then R is rational so $\sigma P - P = \sigma Q - Q$ for any $\sigma \in G$. This implies that Q is also almost rational. Since the points of Σ are cyclotomic, we have $Q \in \Sigma[3]$ (lemma 3).

The conjunction of the previous two paragraphs shows that $J_0(N)_{a.r.t.} \subset C \oplus \Sigma[3]$. To check equality, one notes:

-Rational points are almost rational, so points of C are a.r.

-$\Sigma[3]$ consists of almost rational points: This is because $\Sigma[3]$ is either trivial or isomorphic to μ_3. It's easy to check that points of μ_3 are almost rational.

-A translate of an a.r. point by a rational point is a.r.

We are done.

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