

# Refined class number formulas and Kolyvagin systems

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## ABSTRACT

We use the theory of Kolyvagin systems to prove (most of) a refined class number formula conjectured by Darmon. We show that for every odd prime  $p$ , each side of Darmon's conjectured formula (indexed by positive integers  $n$ ) is “almost” a  $p$ -adic Kolyvagin system as  $n$  varies. Using the fact that the space of Kolyvagin systems is free of rank one over  $\mathbf{Z}_p$ , we show that Darmon's formula for arbitrary  $n$  follows from the case  $n = 1$ , which in turn follows from classical formulas.

## 1. Introduction

In this paper we use the theory of Kolyvagin systems to prove (most of) a conjecture of Darmon from [1].

In [2, Conjecture 4.1], inspired by work of the first author and Tate [7], and of Hayes [4], Gross conjectured a “refined class number formula” for abelian extensions  $K/k$  of global fields. Attached to this extension (and some chosen auxiliary data) there is a generalized Stickelberger element  $\theta_{K/k} \in \mathbf{Z}[G]$ , where  $G := \text{Gal}(K/k)$ , with the property that for every complex-valued character  $\chi$  of  $G$ ,  $\chi(\theta_{K/k})$  is essentially  $L(K/k, \chi, 0)$  (modified by the chosen auxiliary data). Gross' conjectural formula is a congruence for  $\theta_{K/k}$ , modulo a certain specified power of the augmentation ideal of  $\mathbf{Z}[G]$ , in terms of a regulator that Gross defined.

In a very special case, Darmon formulated an analogue of Gross' conjecture involving first derivatives of  $L$ -functions at  $s = 0$ . Suppose  $F$  is a real quadratic field, and  $K_n := F(\mu_n)$  is the extension of  $F$  generated by  $n$ -th roots of unity, with  $n$  prime to the conductor of  $F/\mathbf{Q}$ . Darmon defined a Stickelberger-type element  $\theta'_n \in K_n^\times \otimes \mathbf{Z}[\text{Gal}(K_n/F)]$ , interpolating the first derivatives  $L'(\chi\omega_F, 0)$ , where  $\omega_F$  is the quadratic character attached to  $F/\mathbf{Q}$  and  $\chi$  runs through even Dirichlet characters of conductor  $n$ . Darmon conjectured that  $\theta'_n$  is congruent, modulo a specified power of the augmentation ideal, to a regulator that he defined. See §3 and Conjecture 3.8 below for a precise statement.

Our main result is a proof of Darmon's conjecture “away from the 2-part”. In other words, we prove that the difference of the two sides of Darmon's conjectured congruence is an element of 2-power order.

The idea of our proof is a simple application of the results proven in [5]. For every odd prime  $p$  we show that although neither the left-hand side nor the right-hand of Darmon's conjectured congruence (as  $n$  varies) is a “Kolyvagin system” as defined in [5], each side is *almost* a Kolyvagin system; moreover, both sides fail to be Kolyvagin systems in precisely the same way. That is, we show that the left-hand side and right-hand side form what we call in this paper *pre-Kolyvagin systems* in the sense that they each satisfy the specific set of local and global compatibility relations given in Definition 6.2 below. It seems that pre-Kolyvagin systems are what tend to occur “in nature”, while Kolyvagin systems satisfy a cleaner set of axioms. We show that the two concepts are equivalent,

by constructing (see Proposition 6.5) a natural transformation  $\mathcal{T}$  that turns pre-Kolyvagin systems into Kolyvagin systems and has the properties that:

- $\mathcal{T}$  does not change the term associated to  $n = 1$ , and
- $\mathcal{T}$  is an isomorphism from the  $\mathbf{Z}_p$ -module of pre-Kolyvagin systems to the  $\mathbf{Z}_p$ -module of Kolyvagin systems.

Since it was proved in [5] that (in this situation) the space of Kolyvagin systems is a free  $\mathbf{Z}_p$ -module of rank one, it follows that if two pre-Kolyvagin systems agree when  $n = 1$ , then they agree for every  $n$ . In the case  $n = 1$ , Darmon’s congruence follows from classical formulas for  $L'(\omega_F, 0)$ , so we deduce that (the  $p$ -part, for every odd prime  $p$  of) Darmon’s conjectured congruence formula holds for all  $n$ .

Darmon’s conjecture begs for a generalization. A naive generalization, even just to the case where  $F$  is a real abelian extension of  $\mathbf{Q}$ , is unsuccessful because the definition of Darmon’s regulator does not extend to the case where  $[F : \mathbf{Q}] > 2$ . In a forthcoming paper we will use the ideas and conjectures of [8] to show how both Gross’ and Darmon’s conjectures are special cases of a much more general conjecture. In the current paper we treat only Darmon’s conjecture because it can be presented and proved in a very concrete and explicit manner.

The paper is organized as follows. In §2 we describe our setting and notation, and in §3 we state Darmon’s conjecture and our main result (Theorem 3.9). In §4 we recall some work of Hales [3] on quotients of powers of augmentation ideals, that will enable us to translate the definition of Kolyvagin system given in [5] into a form that will be more useful for our purposes here. In §5 we give the definition of a Kolyvagin system (for the Galois representation  $\mathbf{Z}_p(1) \otimes \omega_F$ ). In §6 we define pre-Kolyvagin system, and give an isomorphism between the space of pre-Kolyvagin systems and the space of Kolyvagin systems. In §7 (resp., §8) we show that the “Stickelberger” side (resp., regulator side) of Darmon’s formula is a pre-Kolyvagin system as  $n$  varies. Finally, in §9 we combine the results of the previous sections to prove Theorem 3.9.

## 2. Setting and notation

Fix once and for all a real quadratic field  $F$ , and let  $f$  be the conductor of  $F/\mathbf{Q}$ . Let  $\omega = \omega_F$  be the quadratic Dirichlet character associated to  $F/\mathbf{Q}$ , and  $\tau$  the nontrivial element of  $\text{Gal}(F/\mathbf{Q})$ . If  $M$  is a  $\text{Gal}(F/\mathbf{Q})$ -module, we let  $M^-$  be the subgroup of elements of  $M$  on which  $\tau$  acts as  $-1$ .

Throughout this paper  $\ell$  will always denote a prime number. Let  $\mathcal{N}$  denote the set of squarefree positive integers prime to  $f$ . If  $n \in \mathcal{N}$  let  $n_+$  be the product of all primes dividing  $n$  that split in  $F/\mathbf{Q}$ , and  $r(n) \in \mathbf{Z}_{\geq 0}$  the number of prime divisors of  $n_+$ :

$$n_+ := \prod_{\ell | n, \omega(\ell)=1} \ell,$$

$$r(n) := \#\{\ell : \ell \mid n_+\} = \#\{\ell : \ell \mid n \text{ and } \ell \text{ splits in } F\}.$$

For every  $n \in \mathcal{N}$  let  $\mu_n$  be the Galois module of  $n$ -th roots of unity in  $\bar{\mathbf{Q}}$ , define

$$\Gamma_n := \text{Gal}(F(\mu_n)/F) \cong \text{Gal}(\mathbf{Q}(\mu_n)/\mathbf{Q}) \cong (\mathbf{Z}/n\mathbf{Z})^\times,$$

and let  $I_n$  denote the augmentation ideal of  $\mathbf{Z}[\Gamma_n]$ , which is generated over  $\mathbf{Z}$  by  $\{\gamma - 1 : \gamma \in \Gamma_n\}$ . There is a natural isomorphism

$$\Gamma_n \cong I_n/I_n^2 \tag{1}$$

defined by sending  $\gamma \in \Gamma_n$  to  $\gamma - 1 \pmod{I_n^2}$ . If  $m \mid n$  then we can view  $\Gamma_m$  either as the quotient  $\text{Gal}(F(\mu_m)/F)$  of  $\Gamma_n$ , or as the subgroup  $\text{Gal}(F(\mu_n)/F(\mu_{n/m}))$ . With the latter identification we

have

$$\Gamma_n = \prod_{\ell|n} \Gamma_\ell, \quad I_n/I_n^2 = \bigoplus_{\ell|n} I_\ell/I_\ell^2$$

the product and the sum taken over primes  $\ell$  dividing  $n$ .

We will usually write the group operation in multiplicative groups such as  $F^\times$  with standard multiplicative notation (for example, with identity element 1). However, when dealing with “mixed” groups such as  $F^\times \otimes I_n^r/I_n^{r+1}$ , we will write the operation additively and use 0 for the identity element.

Fix an embedding  $\bar{\mathbf{Q}} \hookrightarrow \mathbf{C}$ .

### 3. Statement of the conjecture

In this section we state our modified version of Darmon’s conjecture (mostly following [1]) and our main result (Theorem 3.9).

If  $n \in \mathcal{N}$ , let  $\zeta_n \in \mu_n$  be the inverse image of  $e^{2\pi i/n}$  under the chosen embedding  $\bar{\mathbf{Q}} \hookrightarrow \mathbf{C}$ , and define the cyclotomic unit

$$\alpha_n := \prod_{\gamma \in \text{Gal}(\mathbf{Q}(\mu_{nf})/\mathbf{Q}(\mu_n))} \gamma(\zeta_{nf} - 1)^{\omega_F(\gamma)} \in F(\mu_n)^\times$$

and the “first derivative  $\theta$ -element”

$$\theta'_n = \sum_{\gamma \in \Gamma_n} \gamma(\alpha_n) \otimes \gamma \in F(\mu_n)^\times \otimes \mathbf{Z}[\Gamma_n].$$

REMARK 3.1. The element  $\theta'_n$  is an “ $L$ -function derivative evaluator” in the sense that for every even character  $\chi : \Gamma_n \rightarrow \mathbf{C}^\times$ , classical formulas give

$$(\log |\cdot| \otimes \chi)(\theta'_n) := \sum_{\gamma \in \Gamma_n} \chi(\gamma) \log |\gamma(\alpha_n)| = -2L'_n(0, \omega_F \chi)$$

where  $L_n(s, \omega_F \chi)$  is the Dirichlet  $L$ -function with Euler factors at primes dividing  $n$  removed, and  $|\cdot|$  is the absolute value corresponding to our chosen embedding  $\bar{\mathbf{Q}} \hookrightarrow \mathbf{C}$ .

Suppose  $n \in \mathcal{N}$ . Let  $X_n$  be the group of divisors of  $F$  supported above  $n\infty$ , and let  $\mathcal{E}_n := \mathcal{O}_F[1/n]^\times$ , the group of  $n$ -units of  $F$ . We will write the action of  $\mathbf{Z}[\Gamma_n]$  on  $\mathcal{E}_n$  additively, so in particular  $(1 - \tau)\mathcal{E}_n = \{\epsilon/\epsilon^\tau : \epsilon \in \mathcal{E}_n\}$ .

Let  $\lambda_0 \in X_n$  be the archimedean place of  $F$  corresponding to our chosen embedding  $\bar{\mathbf{Q}} \hookrightarrow \mathbf{C}$ .

LEMMA 3.2. Suppose  $n \in \mathcal{N}$ , and let  $r = r(n)$ .

- (i) We have  $X_n^- = X_{n_+}^-$ ,  $\mathcal{E}_n^- = \mathcal{E}_{n_+}^-$ , and  $(1 - \tau)\mathcal{E}_n = (1 - \tau)\mathcal{E}_{n_+}$ .
- (ii) The group  $(1 - \tau)\mathcal{E}_n$  is a free abelian group of rank  $r + 1$ , and is a subgroup of finite index in  $\mathcal{E}_n^-$ .
- (iii) The group  $X_n^-$  is a free abelian group of rank  $r + 1$ . If  $n_+ = \prod_{i=1}^r \ell_i$ , and  $\ell_i = \lambda_i \lambda_i^\tau$ , then  $\{\lambda_0 - \lambda_0^\tau, \lambda_1 - \lambda_1^\tau, \dots, \lambda_r - \lambda_r^\tau\}$  is a basis of  $X_n^-$ .

*Proof.* The only part that is not clear is that  $(1 - \tau)\mathcal{E}_n$  is torsion-free, i.e.,  $-1 \notin (1 - \tau)\mathcal{E}_n$ . Let  $d > 1$  be a squarefree integer such that  $F = \mathbf{Q}(\sqrt{d})$ . If  $x^\tau = -x$ , then  $x/\sqrt{d} \in \bar{\mathbf{Q}}$ , so  $x$  is not a unit at the primes dividing  $d$ . Since  $n$  is prime to  $d$ , we cannot have  $x \in \mathcal{E}_n$ .  $\square$

DEFINITION 3.3. A *standard*  $\mathbf{Z}$ -basis of  $X_n^-$  is a basis of the form described in Lemma 3.2(iii). Given a standard basis of  $X_n^-$ , a  $\mathbf{Z}$ -basis  $\{\epsilon_0, \dots, \epsilon_r\}$  of  $(1 - \tau)\mathcal{E}_n$  will be called *oriented* if the (regulator)

determinant of the logarithmic embedding

$$(1 - \tau)\mathcal{E}_n \longrightarrow X_n^- \otimes \mathbf{R}, \quad \epsilon \mapsto \sum_{\lambda|n_+ \infty} \log |\epsilon|_\lambda \cdot \lambda$$

with respect to the two bases is positive. Concretely, this regulator is the determinant of the matrix whose entry in row  $i$  and column  $j$  is  $\log |\epsilon_j|_{\lambda_i}$ .

REMARK 3.4. Choosing a standard basis of  $X_n^-$  is equivalent to ordering the prime divisors  $\ell_i$  of  $n_+$  and choosing one prime of  $F$  above each  $\ell_i$ .

Any basis of  $(1 - \tau)\mathcal{E}_n$  can be oriented either by reordering the basis, or inverting one of the basis elements.

DEFINITION 3.5. Suppose  $n \in \mathcal{N}$  and  $\lambda$  is a prime of  $F$  dividing  $n_+$ . Define a homomorphism

$$[\cdot]_\lambda^n : F^\times \longrightarrow I_n/I_n^2$$

by

$$[x]_\lambda^n = [x, F_\lambda(\boldsymbol{\mu}_n)/F_\lambda] - 1 \pmod{I_n^2}$$

where  $[x, F_\lambda(\boldsymbol{\mu}_n)/F_\lambda] \in \Gamma_n$  is the local Artin symbol. Note that if  $\text{ord}_\lambda(x) = 0$ , then  $[x, F_\lambda(\boldsymbol{\mu}_n)/F_\lambda]$  belongs to the inertia group  $\Gamma_\ell \subset \Gamma_n$ , so  $[x]_\lambda^n = [x]_\lambda^\ell \in I_\ell/I_\ell^2$  and  $[x]_\lambda^{n/\ell} = 0$ . In general, if  $d \mid n$  then

$$[x]_\lambda^n = [x]_\lambda^d + [x]_\lambda^{n/d} \in I_d/I_d^2 \oplus I_{n/d}/I_{n/d}^2 = I_n/I_n^2.$$

DEFINITION 3.6. (See [1, p. 308].) Suppose  $n \in \mathcal{N}$ , and let  $r = r(n)$ . Choose a standard basis  $\{\lambda_0 - \lambda_0^\tau, \dots, \lambda_r - \lambda_r^\tau\}$  of  $X_n^-$  and an oriented basis  $\{\epsilon_0, \dots, \epsilon_r\}$  of  $(1 - \tau)\mathcal{E}_n$ , and define the regulator  $R_n \in \mathcal{E}_n^- \otimes I_n^r/I_n^{r+1}$  by

$$R_n := \begin{vmatrix} \epsilon_0 & \epsilon_1 & \cdots & \epsilon_r \\ [\epsilon_0]_{\lambda_1}^n & [\epsilon_1]_{\lambda_1}^n & \cdots & [\epsilon_r]_{\lambda_1}^n \\ \vdots & \vdots & & \vdots \\ [\epsilon_0]_{\lambda_r}^n & [\epsilon_1]_{\lambda_r}^n & \cdots & [\epsilon_r]_{\lambda_r}^n \end{vmatrix} \in (1 - \tau)\mathcal{E}_n \otimes I_n^r/I_n^{r+1}.$$

This determinant, and the ones that follow below, are meant to be evaluated by expanding by minors along the top row, i.e.,

$$R_n := \sum_{j=0}^r (-1)^j \epsilon_j \otimes \det(A_{1j}) \tag{2}$$

where  $A_{1j}$  is the  $r \times r$  matrix (with entries in  $I_n/I_n^2$ ) obtained by removing the first row and  $j$ -th column of the matrix above.

Note that this definition of  $R_n$  does not depend on the choice of  $\mathbf{Z}$ -bases. The possible ambiguity of  $\pm 1$  is removed by requiring that the basis of  $(1 - \tau)\mathcal{E}_n$  be oriented.

Let  $h_n$  denote the “ $n$ -class number” of  $F$ , i.e., the order of the ideal class group  $\text{Pic}(\mathcal{O}_F[1/n])$ . For the rest of this section we write simply  $r$  instead of  $r(n)$ .

THEOREM 3.7 (Darmon [1, Theorem 4.2]). *For every  $n \in \mathcal{N}$ , we have*

$$\theta'_n \in F(\boldsymbol{\mu}_n)^\times \otimes I_n^r.$$

For  $n \in \mathcal{N}$ , let  $\tilde{\theta}'_n$  denote the image of  $\theta'_n$  in  $F(\boldsymbol{\mu}_n)^\times \otimes I_n^r/I_n^{r+1}$ . Let  $s$  be the number of prime divisors of  $n/n_+$ ; we continue to denote by  $r$  the number of prime factors of  $n_+$ .

The following is a slightly modified version of Darmon’s “leading term” conjecture [1, Conjecture 4.3].

CONJECTURE 3.8. *For every  $n \in \mathcal{N}$ , we have*

$$\tilde{\theta}'_n = -2^s h_n R_n \quad \text{in } (F(\boldsymbol{\mu}_n)^\times / \{\pm 1\}) \otimes I_n^r / I_n^{r+1}.$$

The main theorem of this paper is the following.

THEOREM 3.9. *For every  $n \in \mathcal{N}$ , we have*

$$\tilde{\theta}'_n = -2^s h_n R_n \quad \text{in } F(\boldsymbol{\mu}_n)^\times \otimes I_n^r / I_n^{r+1} \otimes \mathbf{Z}[1/2].$$

In other words, the  $p$ -part of Conjecture 3.8 holds for every odd prime  $p$ ; in still other words,  $\tilde{\theta}'_n + 2^s h_n R_n$  has 2-power order in  $F(\boldsymbol{\mu}_n)^\times \otimes I_n^r / I_n^{r+1}$ .

A key step in the proof of Theorem 3.9 is the following observation.

PROPOSITION 3.10 (Darmon [1, Theorem 4.5(1)]). *Conjecture 3.8 holds if  $n = 1$ .*

*Proof.* When  $n = 1$  we have  $r = 0$ ,  $I_n^r / I_n^{r+1} = \mathbf{Z}$ ,  $\tilde{\theta}'_1 = \theta'_1 = \alpha_1 \in \mathcal{O}_F^\times$ , and  $R_1 = \epsilon / \epsilon^\tau$ , where  $\epsilon$  is a generator of  $\mathcal{O}_F^\times / \{\pm 1\}$  and  $|\epsilon / \epsilon^\tau| = |\epsilon|^2 > 1$  at our specified archimedean place. Dirichlet's analytic class number formula shows that

$$-\frac{1}{2} \log |\alpha_1| = L'(0, \omega_F) = h_F \log |\epsilon| = \frac{1}{2} h_F \log |\epsilon / \epsilon^\tau|$$

where  $h_F = h_1$  is the class number of  $F$ . Hence  $\alpha_1 = \pm(\epsilon / \epsilon^\tau)^{-h_F}$  in  $\mathcal{O}_F^\times$ .  $\square$

REMARKS 3.11. (i) In Darmon's formulation [1, Conjecture 4.3], the regulator  $R_n$  was defined with respect to a basis of  $\mathcal{E}_n^- / \{\pm 1\}$  instead of  $(1 - \tau)\mathcal{E}_n$ , and there was an extra factor of 2 on the right-hand side. This agrees with Conjecture 3.8 if and only if  $[\mathcal{E}_n^- : \pm(1 - \tau)\mathcal{E}_n] = 2$ , i.e., if and only if  $-1 \notin \mathbf{N}_{F/\mathbf{Q}}\mathcal{E}_n$ .

(ii) The ambiguity of  $\pm 1$  in Conjecture 3.8 is necessary. Namely, even when  $n = 1$ , we may only have  $\theta'_1 = h_1 R_1$  in  $\mathcal{O}_F^\times / \{\pm 1\}$ . Since  $\alpha_1$  is always positive (it is a norm from a CM field to  $F$ ), the proof of Proposition 3.10 shows that  $\tilde{\theta}'_1 \neq -h_1 R_1$  in  $F^\times$  when  $h_F$  is odd and  $\mathcal{O}_F^\times$  has a unit of norm  $-1$ . Note that in this case  $\tilde{\theta}'_1$  and  $-h_1 R_1$  differ (multiplicatively) by an element of order 2 in  $F^\times$ , so the discrepancy disappears when we tensor with  $\mathbf{Z}[1/2]$ .

#### 4. Augmentation quotients

DEFINITION 4.1. Suppose  $n \in \mathcal{N}$ , and let  $r = r(n)$ . Let  $\mathcal{I}_n^{\text{new}} \subset I_n^r / I_n^{r+1}$  be the (cyclic) subgroup generated by monomials  $\prod_{\ell|n_+} (\gamma_\ell - 1)$  with  $\gamma_\ell \in \Gamma_\ell$ . Let  $\mathcal{I}_n^{\text{old}} \subset I_n^r / I_n^{r+1}$  be the subgroup generated by monomials  $\prod_{i=1}^r (\gamma_i - 1)$  where each  $\gamma_i \in \Gamma_{\ell_i}$  for some  $\ell_i$  dividing  $n$ , and  $\{\ell_1, \dots, \ell_r\} \neq \{\ell : \ell \mid n_+\}$  (i.e., either one of the  $\ell_i$  divides  $n/n_+$ , or  $\ell_i = \ell_j$  for some  $i \neq j$ ). If  $n = d_1 d_2$  then there is a natural identification  $\mathcal{I}_n^{\text{new}} = \mathcal{I}_{d_1}^{\text{new}} \mathcal{I}_{d_2}^{\text{new}} \subset I_n^r / I_n^{r+1}$ , and if  $n = \ell$  is prime then  $\mathcal{I}_\ell^{\text{new}} = I_\ell / I_\ell^2$  and  $\mathcal{I}_\ell^{\text{old}} = 0$ .

If  $d \mid n$ , let

$$\pi_d : \mathbf{Z}[\Gamma_n] \twoheadrightarrow \mathbf{Z}[\Gamma_d] \hookrightarrow \mathbf{Z}[\Gamma_n]$$

denote the composition of the natural maps. We also write  $\pi_d$  for the induced map on  $I_n^k / I_n^{k+1}$  for  $k \geq 0$ .

The following proposition is based on work of Hales [3].

PROPOSITION 4.2. *Suppose  $n \in \mathcal{N}$ , and  $r = r(n)$ . Then:*

- (i)  $I_n^r / I_n^{r+1} = \mathcal{I}_n^{\text{new}} \oplus \mathcal{I}_n^{\text{old}}$ .
- (ii) If  $d \mid n_+$  and  $d > 1$ , then  $\pi_{n/d}(\mathcal{I}_n^{\text{new}}) = 0$  and  $\pi_{n/d}(I_n^r / I_n^{r+1}) \subset \mathcal{I}_n^{\text{old}}$ .
- (iii)  $\mathcal{I}_n^{\text{new}} = \{v \in I_n^r / I_n^{r+1} : \pi_{n/\ell}(v) = 0 \text{ for every } \ell \text{ dividing } n_+\}$ .

(iv) The map  $\otimes_{\ell|n_+} \Gamma_\ell \rightarrow \mathcal{I}_n^{\text{new}}$  defined by  $\otimes_{\ell|n_+} \gamma_\ell \mapsto \prod_{\ell|n_+} (\gamma_\ell - 1)$  is an isomorphism.

*Proof.* Let  $A_n$  be the polynomial ring  $\mathbf{Z}[Y_\ell : \ell \mid n]$  with one variable  $Y_\ell$  for each prime  $\ell$  dividing  $n$ . Fix a generator  $\sigma_\ell$  of  $\Gamma_\ell$  for every  $\ell$  dividing  $n$ , and define a map  $A_n \rightarrow \mathbf{Z}[\Gamma_n]$  by sending  $Y_\ell \mapsto \sigma_\ell - 1$ . By Corollary 2 of [3], this map induces an isomorphism from the homogeneous degree- $r$  part of  $A_n/(J_n + J'_n)$  to  $I_n^r/I_n^{r+1}$ , where  $J_n$  is the ideal of  $A_n$  generated by  $\{(\ell - 1)Y_\ell : \ell \mid n\}$ , and  $J'_n$  is the ideal generated by certain other explicit homogeneous relations (see [3, Lemma 2]). The only fact we need about these “extra” relations is:

if  $f \in J'_n$ , then every monomial that occurs in  $f$  is divisible by the square of some  $Y_\ell$ . (3)

Note that  $\mathcal{I}_n^{\text{new}}$  is the image in  $I_n^r/I_n^{r+1}$  of the subgroup of  $A_n/(J_n + J'_n)$  generated by  $\mathbf{Y}_n$ , where  $\mathbf{Y}_n := \prod_{\ell|n_+} Y_\ell$ . Similarly,  $\mathcal{I}_n^{\text{old}}$  is the image of the subgroup generated by all other monomials of degree  $r$ . By (3),  $\mathbf{Y}_n$  does not occur in any of the relations in  $J'_n$ , and assertion (i) follows.

Assertion (ii) is clear, since  $\pi_{n/d}$  kills those monomials that include  $(\gamma - 1)$  with  $\gamma \in \Gamma_\ell$  for  $\ell$  dividing  $d$ , and leaves the other monomials unchanged.

Fix  $v \in I_n^r/I_n^{r+1}$ . If  $v \in \mathcal{I}_n^{\text{new}}$  and  $\ell \mid n_+$ , then  $\pi_{n/\ell}(v) = 0$  by (ii). Conversely, suppose that  $\pi_{n/\ell}(v) = 0$  for every  $\ell$  dividing  $n_+$ . Choose  $f \in A_n$  homogeneous of degree  $r$  representing  $v$ , and suppose  $f$  has the minimum number of monomials among all representatives of  $v$ . We will show that  $\mathbf{Y}_n \mid f$ , and hence  $v \in \mathcal{I}_n^{\text{new}}$ .

Fix a prime  $\ell$  dividing  $n_+$ . The map  $\pi_{n/\ell} : \mathbf{Z}[\Gamma_n] \rightarrow \mathbf{Z}[\Gamma_{n/\ell}] \hookrightarrow \mathbf{Z}[\Gamma_n]$  corresponds to the map  $A_n \rightarrow A_n$  defined by setting  $Y_\ell = 0$ . Since  $\pi_{n/\ell}(v) = 0$ , substituting  $Y_\ell = 0$  in  $f$  gives a relation in  $J_n + J'_n$ , i.e.,  $f = Y_\ell \cdot g + h$  where  $g$  is homogeneous of degree  $r - 1$ ,  $h \in J_n + J'_n$ , and  $Y_\ell$  does not occur in  $h$ . But then  $Y_\ell \cdot g$  represents  $v$ , so the minimality assumption on  $f$  implies that  $h = 0$ . Therefore  $Y_\ell \mid f$  for every  $\ell$  dividing  $n_+$ , so  $\mathbf{Y}_n \mid f$  and  $v \in \mathcal{I}_n^{\text{new}}$ . This proves (iii).

Let  $g := \gcd(\{\ell - 1 : \ell \mid n_+\})$ . Then  $g\mathbf{Y}_n \in J_n$ . It follows from (3) that the monomial  $\mathbf{Y}_n$  only occurs in elements of  $J_n + J'_n$  with coefficients divisible by  $g$ . Therefore  $\mathcal{I}_n^{\text{new}}$  is cyclic of order  $g$ , and so is  $\otimes_{\ell|n_+} \Gamma_\ell$ . Clearly the map  $\otimes_{\ell|n_+} \Gamma_\ell \rightarrow \mathcal{I}_n^{\text{new}}$  of (iv) is surjective, so it must be an isomorphism.  $\square$

If  $v \in I_n^r/I_n^{r+1}$ , let  $\langle v \rangle_n^{\text{new}}$  denote the projection of  $v$  to  $\mathcal{I}_n^{\text{new}}$  under the splitting of Proposition 4.2(i). We will use the following lemma without explicit reference in some of our computations in §6 and §8. Its proof is left as an exercise.

LEMMA 4.3. Suppose  $d \mid n$ ,  $v \in \mathcal{I}_{n/d}^{\text{new}}$ , and  $w \in I_n^{r(d)}/I_n^{r(d)+1}$ . Then

$$\langle vw \rangle_n^{\text{new}} = \langle v\pi_d(w) \rangle_n^{\text{new}} = v\langle \pi_d(w) \rangle_d^{\text{new}}.$$

## 5. Kolyvagin systems

Fix an odd prime  $p$ . To prove Theorem 3.9 we need to introduce Kolyvagin systems, as defined in [5]. (See in particular [5, §6.1], and also [6], for the case of Kolyvagin systems associated to even Dirichlet characters that we use here.)

Let  $\hat{F}^\times$  denote the  $p$ -adic completion of  $F^\times$ . Similarly, for every rational prime  $\ell$  let  $F_\ell := F \otimes \mathbf{Q}_\ell$ ,  $\mathcal{O}_\ell := \mathcal{O}_F \otimes \mathbf{Z}_\ell$ , and define  $\hat{F}_\ell^\times$  and  $\hat{\mathcal{O}}_\ell^\times$  to be their  $p$ -adic completions. We define the “finite subgroup”  $\hat{F}_{\ell,f}^\times$  to be the “unit part” of  $\hat{F}_\ell^\times$

$$\hat{F}_{\ell,f}^\times := \hat{\mathcal{O}}_\ell^\times \subset \hat{F}_\ell^\times.$$

If  $\ell = \lambda\lambda^\tau$  splits in  $F$ , define the “transverse subgroup”  $\hat{F}_{\ell,\text{tr}}^\times \subset \hat{F}_\ell^\times$  to be the (closed) subgroup generated by  $(\ell, 1)$  and  $(1, \ell)$ , where we identify  $F_\ell^\times$  with  $F_\lambda^\times \times F_{\lambda^\tau}^\times \cong \mathbf{Q}_\ell^\times \times \mathbf{Q}_\ell^\times$ . Then we have a

canonical splitting  $\hat{F}_\ell^\times = \hat{F}_{\ell,f}^\times \times \hat{F}_{\ell,\text{tr}}^\times$ , and since  $p$  is odd

$$(\hat{F}_\ell^\times)^- = (\hat{F}_{\ell,f}^\times)^- \times (\hat{F}_{\ell,\text{tr}}^\times)^-. \quad (4)$$

DEFINITION 5.1. If  $\ell \neq p$  splits in  $F$ , define the *finite-singular isomorphism*

$$\phi_\ell^{\text{fs}} : (\hat{F}_{\ell,f}^\times)^- \xrightarrow{\sim} (\hat{F}_{\ell,\text{tr}}^\times)^- \otimes I_\ell/I_\ell^2$$

by

$$\begin{aligned} \phi_\ell^{\text{fs}}(x) &= (\ell, 1) \otimes ([x_\lambda, F_\lambda(\boldsymbol{\mu}_\ell)/F_\lambda] - 1) + (1, \ell) \otimes ([x_{\lambda^\tau}, F_{\lambda^\tau}(\boldsymbol{\mu}_\ell)/F_{\lambda^\tau}] - 1) \\ &= (\ell, \ell^{-1}) \otimes ([x_\lambda, F_\lambda(\boldsymbol{\mu}_\ell)/F_\lambda] - 1) \end{aligned}$$

where  $x = (x_\lambda, x_{\lambda^\tau}) \in \hat{F}_\lambda^\times \times \hat{F}_{\lambda^\tau}^\times = \hat{\mathbf{Q}}_\ell^\times \times \hat{\mathbf{Q}}_\ell^\times$  with  $x_{\lambda^\tau} = x_\lambda^{-1} \in \hat{\mathbf{Z}}_\ell^\times$ , and  $[\cdot, F_\lambda(\boldsymbol{\mu}_\ell)/F_\lambda]$  is the local Artin symbol. (Concretely, note that if  $u \in \mathbf{Z}_\ell^\times$  then  $[u, F_\lambda(\boldsymbol{\mu}_\ell)/F_\lambda]$  is the automorphism in  $\Gamma_\ell$  that sends  $\zeta_\ell$  to  $\zeta_\ell^{u^{-1}}$ .) Then  $\phi_\ell^{\text{fs}}$  is a well-defined isomorphism (both the domain and range are free of rank one over  $\mathbf{Z}_p/(\ell-1)\mathbf{Z}_p$ ), independent of the choice of  $\lambda$  versus  $\lambda^\tau$ .

DEFINITION 5.2. Let  $\mathcal{N}_p := \{n \in \mathcal{N} : p \nmid n\}$ . A *Kolyvagin system*  $\boldsymbol{\kappa}$  (for the Galois representation  $\mathbf{Z}_p(1) \otimes \omega_F$ ) is a collection

$$\{\kappa_n \in (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}} : n \in \mathcal{N}_p\}$$

satisfying the following properties for every rational prime  $\ell$ . Let  $(\kappa_n)_\ell$  denote the image of  $\kappa_n$  in  $(\hat{F}_\ell^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ .

- (i) If  $\ell \nmid n$ , then  $(\kappa_n)_\ell \in (\hat{F}_{\ell,f}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ .
- (ii) If  $\ell \mid n_+$ , then  $(\kappa_n)_\ell = (\phi_\ell^{\text{fs}} \otimes 1)(\kappa_{n/\ell, \ell})$ .
- (iii) If  $\ell \mid n/n_+$ , then  $\kappa_n = \kappa_{n/\ell}$ .

Let  $\mathbf{KS}(F)$  denote the  $\mathbf{Z}_p$ -module of Kolyvagin systems for  $\mathbf{Z}_p(1) \otimes \omega_F$ .

REMARK 5.3. Let  $\mathcal{N}_p^+ := \{n \in \mathcal{N}_p : \text{all } \ell \mid n \text{ split in } F/\mathbf{Q}\}$ . In [5], a Kolyvagin system was defined to be a collection of classes  $\{\kappa_n \in (\hat{F}_\ell^\times)^- \otimes (\otimes_{\ell \mid n} \Gamma_\ell) : n \in \mathcal{N}_p^+\}$ , and  $\phi_\ell^{\text{fs}}$  took values in  $(\hat{F}_{\ell,\text{tr}}^\times)^- \otimes \Gamma_\ell$ . We use Proposition 4.2(iv) to replace  $\otimes_{\ell \mid n} \Gamma_\ell$  by  $\mathcal{I}_n^{\text{new}}$  and (1) to replace  $\Gamma_\ell$  by  $I_\ell/I_\ell^2$ , which will be more convenient for our purposes here. Also, a Kolyvagin system  $\{\kappa_n : n \in \mathcal{N}_p^+\}$  as in [5] extends uniquely to  $\{\kappa_n : n \in \mathcal{N}_p\}$  simply by setting  $\kappa_n := \kappa_{n_+}$  for  $n \in \mathcal{N}_p - \mathcal{N}_p^+$ .

The following theorem is the key to our proof of Theorem 3.9.

THEOREM 5.4. Suppose  $\boldsymbol{\kappa}, \boldsymbol{\kappa}' \in \mathbf{KS}(F)$ . If  $\kappa_1 = \kappa'_1$ , then  $\kappa_n = \kappa'_n$  for every  $n \in \mathcal{N}_p$ .

*Proof.* We follow §6.1 of [5], with  $R = \mathbf{Z}_p$ ,  $\rho = \omega_F$ ,  $T = \mathbf{Z}_p(1) \otimes \omega_F$ , and with the Selmer structure denoted  $\mathcal{F}$  in [5]. By Lemma 6.1.5 and Proposition 6.1.6 of [5], the hypotheses needed to apply the results of §5.2 of [5] all hold, and the core rank of  $T$  is 1.

By Theorem 5.2.10(ii) of [5],  $\mathbf{KS}(F)$  is a free  $\mathbf{Z}_p$ -module of rank one. Therefore (switching  $\boldsymbol{\kappa}$  and  $\boldsymbol{\kappa}'$  if necessary) there is an  $a \in \mathbf{Z}_p$  such that  $\boldsymbol{\kappa}' = a\boldsymbol{\kappa}$ , i.e.,  $\kappa'_n = a\kappa_n$  for every  $n \in \mathcal{N}_p$ . If  $\boldsymbol{\kappa}$  is identically zero, then so is  $\boldsymbol{\kappa}'$  and we are done. If  $\boldsymbol{\kappa}$  is not identically zero, then (since the ideal class group of  $F$  is finite) Theorem 5.2.12(v) of [5] shows that  $\kappa_1 \neq 0$ . Since  $\kappa'_1 = \kappa_1$  in the torsion-free  $\mathbf{Z}_p$ -module  $(\hat{F}^\times)^-$  (in fact property (i) above shows that  $\kappa_1 \in (\mathcal{O}_F^\times \otimes \mathbf{Z}_p)^-$ ), we must have  $a = 1$ .  $\square$

## 6. Pre-Kolyvagin systems

Keep the fixed odd prime  $p$ . The right-hand and left-hand sides of Conjecture 3.8 are “almost” Kolyvagin systems. If they were Kolyvagin systems, then since they agree when  $n = 1$  (Proposition 3.10), they would agree for all  $n$  by Theorem 5.4, and Theorem 3.9 would be proved.

In this section we define what we call “pre-Kolyvagin systems”, and show that a pre-Kolyvagin system can be transformed into a Kolyvagin system. Using Theorem 5.4, we deduce (Corollary 6.6 below) that if two pre-Kolyvagin systems agree when  $n = 1$ , then they agree for every  $n$ . In §7 and §8, respectively, we will show that the left- and right-hand sides of Conjecture 3.8 are pre-Kolyvagin systems. Then Theorem 3.9 will follow from Corollary 6.6 and Proposition 3.10.

If  $x \in (\hat{F}^\times)^- \otimes I_n^r/I_n^{r+1}$ , let  $x_\ell$  denote the image of  $x$  in  $(\hat{F}_\ell^\times)^- \otimes I_n^r/I_n^{r+1}$ , and if  $\ell \in \mathcal{N}_p$  splits in  $F/\mathbf{Q}$ , let  $x_{\ell,f} \in (\hat{F}_{\ell,f}^\times)^- \otimes I_n^r/I_n^{r+1}$  and  $x_{\ell,\text{tr}} \in (\hat{F}_{\ell,\text{tr}}^\times)^- \otimes I_n^r/I_n^{r+1}$  denote the projections of  $x_\ell$  induced by the splitting (4). Let  $\langle x \rangle_n^{\text{new}} \in (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$  denote the projection of  $x$  induced by the splitting of Proposition 4.2(i), and similarly for  $\langle x_\ell \rangle_n^{\text{new}}$  and  $\langle x_{\ell,f} \rangle_n^{\text{new}}$ .

**DEFINITION 6.1.** If  $n \in \mathcal{N}$  and  $d = \prod_{i=1}^t \ell_i$  divides  $n_+$ , let  $M_{n,d} = (m_{ij})$  be the  $t \times t$  matrix with entries in  $I_n/I_n^2$

$$m_{ij} = \begin{cases} \pi_{n/d}(\text{Fr}_{\ell_i} - 1) & \text{if } i = j, \\ \pi_{\ell_j}(\text{Fr}_{\ell_i} - 1) & \text{if } i \neq j. \end{cases}$$

We let  $M_d := M_{d,d}$ , where  $\pi_1(\text{Fr}_\ell - 1)$  is understood to be zero, so that all diagonal entries of  $M_d$  are zero. Define

$$\mathcal{D}_{n,d} := \det(M_{n,d}) \in I_n^t/I_n^{t+1}, \quad \mathcal{D}_d := \det(M_d) \in \mathcal{I}_d^{\text{new}} \subset I_n^t/I_n^{t+1}.$$

By convention we let  $\mathcal{D}_{n,1} = \mathcal{D}_1 = 1$ . Note that  $\mathcal{D}_{n,d}$  and  $\mathcal{D}_d$  are independent of the ordering of the prime factors of  $d$ .

**DEFINITION 6.2.** A *pre-Kolyvagin system*  $\kappa$  (for  $\mathbf{Z}_p(1) \otimes \omega_F$ ) is a collection

$$\{\kappa_n \in (\hat{F}^\times)^- \otimes I_n^r/I_n^{r+1} : n \in \mathcal{N}_p\}$$

where  $r = r(n)$ , satisfying the following properties for every rational prime  $\ell$ :

- (i) If  $\ell \nmid n$ , then  $(\kappa_n)_\ell \in (\hat{F}_{\ell,f}^\times)^- \otimes I_n^r/I_n^{r+1}$ .
- (ii) If  $\ell \mid n_+$ , then  $(1 \otimes \pi_{n/\ell})\kappa_n = \kappa_{n/\ell} \pi_{n/\ell}(1 - \text{Fr}_\ell)$ .
- (iii) If  $\ell \mid n_+$ , then  $\langle (\kappa_n)_{\ell,\text{tr}} \rangle_n^{\text{new}} = (\phi_\ell^{\text{fs}} \otimes 1)(\langle (\kappa_{n/\ell})_\ell \rangle_{n/\ell}^{\text{new}})$ .
- (iv) If  $\ell \mid n_+$ , then  $\sum_{d \mid n_+} \langle (\kappa_{n/d})_{\ell,f} \rangle_{n/d}^{\text{new}} \mathcal{D}_d = 0$ .
- (v) If  $\ell \mid n/n_+$ , then  $\langle \kappa_n \rangle_n^{\text{new}} = \langle \kappa_{n/\ell} \rangle_{n/\ell}^{\text{new}}$ .

Let  $\mathbf{PKS}(F)$  denote the  $\mathbf{Z}_p$ -module of pre-Kolyvagin systems for  $\mathbf{Z}_p(1) \otimes \omega_F$ .

**DEFINITION 6.3.** If  $\kappa = \{\kappa_n : n \in \mathcal{N}_p\}$  is a pre-Kolyvagin system, define  $\tilde{\kappa} = \{\tilde{\kappa}_n : n \in \mathcal{N}_p\}$  by

$$\tilde{\kappa}_n := \sum_{d \mid n_+} \kappa_{n/d} \mathcal{D}_{n,d}.$$

**LEMMA 6.4.** Suppose  $n \in \mathcal{N}_p$  and  $d \mid n$ .

- (i) If  $\ell \mid d$  then  $\pi_{n/\ell}(\mathcal{D}_{n,d}) = \pi_{n/d}(\text{Fr}_\ell - 1)\mathcal{D}_{n/\ell,d/\ell}$ .
- (ii) If  $\ell \nmid d$  then  $\pi_{n/\ell}(\mathcal{D}_{n,d}) = \mathcal{D}_{n/\ell,d}$ .
- (iii)  $\pi_d(\mathcal{D}_{n,d}) = \mathcal{D}_d \in \mathcal{I}_d^{\text{new}}$ .

*Proof.* Suppose  $\ell \mid d$ . The column of  $\pi_{n/\ell}(M_{n,d})$  corresponding to  $\ell$  consists of all zeros except for  $\pi_{n/d}(\text{Fr}_\ell - 1)$  on the diagonal. The first assertion follows from this, and (ii) and (iii) follow directly from the definition.  $\square$

**PROPOSITION 6.5.** The map  $\kappa \mapsto \tilde{\kappa}$  of Definition 6.3 is a  $\mathbf{Z}_p$ -module isomorphism  $\mathbf{PKS}(F) \xrightarrow{\sim} \mathbf{KS}(F)$  between free  $\mathbf{Z}_p$ -modules of rank one.



*Proof.* The  $\mathbf{Z}_p$ -linearity is clear. The injectivity is clear as well, since it follows easily by induction that if  $\tilde{\kappa}_n = 0$  for all  $n$ , then  $\kappa_n = 0$  for all  $n$ .

We next show that if  $\kappa$  is a pre-Kolyvagin system, then  $\tilde{\kappa}$  is a Kolyvagin system. In other words, we need to show for every  $n \in \mathcal{N}_p$  that

- (a)  $\tilde{\kappa}_n \in (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ ,
- (b) if  $\ell \nmid n$  then  $(\tilde{\kappa}_n)_\ell \in (\hat{F}_{\ell, \text{f}}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ ,
- (c) if  $\ell \mid n_+$  then  $(\tilde{\kappa}_n)_{\ell, \text{tr}} = (\phi_\ell^{\text{fs}} \otimes 1)((\kappa_{n/\ell})_\ell)$ ,
- (d) if  $\ell \mid n_+$  then  $(\tilde{\kappa}_n)_{\ell, \text{f}} = 0$ ,
- (e) if  $\ell \mid n/n_+$  then  $\tilde{\kappa}_n = \tilde{\kappa}_{n/\ell}$ .

Fix  $n \in \mathcal{N}_p$ , and suppose that  $\ell \mid n_+$ . Then

$$\begin{aligned} (1 \otimes \pi_{n/\ell})(\tilde{\kappa}_n) &= \sum_{d \mid n_+, \ell \nmid d} (1 \otimes \pi_{n/\ell})(\kappa_{n/d} \mathcal{D}_{n,d}) + \sum_{d \mid n_+, \ell \mid d} (1 \otimes \pi_{n/\ell})(\kappa_{n/d} \mathcal{D}_{n,d}) \\ &= \sum_{d \mid (n_+/\ell)} \kappa_{n/(d\ell)} \pi_{n/\ell}(\mathcal{D}_{n,d\ell}) + (1 \otimes \pi_{n/(d\ell)})(\kappa_{n/d}) \pi_{n/\ell}(\mathcal{D}_{n,d}). \end{aligned}$$

Fix a divisor  $d$  of  $n_+/\ell$ . By Lemma 6.4(i),

$$\kappa_{n/(d\ell)} \pi_{n/\ell}(\mathcal{D}_{n,d\ell}) = \kappa_{n/(d\ell)} \pi_{n/(d\ell)}(\text{Fr}_\ell - 1) \mathcal{D}_{n/\ell, d}.$$

Also,  $(1 \otimes \pi_{n/(d\ell)})(\kappa_{n/d}) = \kappa_{n/(d\ell)} \pi_{n/(d\ell)}(1 - \text{Fr}_\ell)$  by Definition 6.2(ii), so by Lemma 6.4(ii)

$$(1 \otimes \pi_{n/(d\ell)})(\kappa_{n/d}) \pi_{n/\ell}(\mathcal{D}_{n,d}) = \kappa_{n/(d\ell)} \pi_{n/(d\ell)}(1 - \text{Fr}_\ell) \mathcal{D}_{n/\ell, d}.$$

Thus  $(1 \otimes \pi_{n/\ell})(\tilde{\kappa}_n) = 0$  for every  $\ell$  dividing  $n$ . Since  $(\hat{F}^\times)^-$  is a free  $\mathbf{Z}_p$ -module, it follows from Proposition 4.2(iii) that  $\tilde{\kappa}_n \in (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ . This is property (a) above.

By (a), and using that  $\pi_d(\mathcal{D}_{n,d}) \in \mathcal{I}_d^{\text{new}}$ , we have

$$\tilde{\kappa}_n = \langle \tilde{\kappa}_n \rangle_n^{\text{new}} = \sum_{d \mid n_+} \langle \kappa_{n/d} \rangle_{n/d}^{\text{new}} \pi_d(\mathcal{D}_{n,d}).$$

If  $\ell \nmid n$ , then property (i) of Definition 6.2 of a pre-Kolyvagin system shows that  $\langle (\kappa_{n/d})_\ell \rangle_{n/d}^{\text{new}} \in (\hat{F}_{\ell, \text{f}}^\times)^- \otimes \mathcal{I}_{n/d}^{\text{new}}$  for every  $d$ , so  $(\tilde{\kappa}_n)_\ell \in (\hat{F}_{\ell, \text{f}}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ . This is (b).

Now suppose  $\ell \mid n_+$ . For (c), using property (i) of Definition 6.2 we have

$$(\tilde{\kappa}_n)_{\ell, \text{tr}} = \sum_{d \mid n_+} (\kappa_{n/d})_{\ell, \text{tr}} \mathcal{D}_{n,d} = \sum_{d \mid (n_+/\ell)} (\kappa_{n/d})_{\ell, \text{tr}} \mathcal{D}_{n,d}.$$

Projecting into  $\mathcal{I}_n^{\text{new}}$ , and using (a), (ii) of Definition 6.2, and Lemma 6.4(ii), we have

$$\begin{aligned} (\tilde{\kappa}_n)_{\ell, \text{tr}} &= \langle (\tilde{\kappa}_n)_{\ell, \text{tr}} \rangle_n^{\text{new}} = \sum_{d \mid (n_+/\ell)} \langle (\kappa_{n/d})_{\ell, \text{tr}} \mathcal{D}_{n,d} \rangle_n^{\text{new}} \\ &= \sum_{d \mid (n_+/\ell)} \langle (\phi_\ell^{\text{fs}} \otimes 1)((\kappa_{n/(d\ell)})_\ell) \pi_{n/\ell}(\mathcal{D}_{n,d}) \rangle_n^{\text{new}} \\ &= \sum_{d \mid (n_+/\ell)} \langle (\phi_\ell^{\text{fs}} \otimes 1)((\kappa_{n/(d\ell)})_\ell) \mathcal{D}_{n/\ell, d} \rangle_n^{\text{new}} \\ &= \langle (\phi_\ell^{\text{fs}} \otimes 1)(\tilde{\kappa}_{n/\ell}) \rangle_n^{\text{new}} = (\phi_\ell^{\text{fs}} \otimes 1) \langle \tilde{\kappa}_{n/\ell} \rangle_{n/\ell}^{\text{new}} = (\phi_\ell^{\text{fs}} \otimes 1)(\tilde{\kappa}_{n/\ell}). \end{aligned}$$

This is (c). For (d), using (a), Lemma 6.4(iii), and (iv) of Definition 6.2 we have

$$(\tilde{\kappa}_n)_{\ell, \text{f}} = \langle (\tilde{\kappa}_n)_{\ell, \text{f}} \rangle_n^{\text{new}} = \sum_{d \mid n_+} \langle (\kappa_{n/d})_{\ell, \text{f}} \rangle_{n/d}^{\text{new}} \langle \pi_d(\mathcal{D}_{n,d}) \rangle_d^{\text{new}} = \sum_{d \mid n_+} \langle (\kappa_{n/d})_{\ell, \text{f}} \rangle_{n/d}^{\text{new}} \mathcal{D}_d = 0.$$

Finally, suppose that  $\ell \mid n/n_+$ . Using Definition 6.2(v) and property (a) above,

$$\tilde{\kappa}_n = \langle \tilde{\kappa}_n \rangle_n^{\text{new}} = \sum_{d \mid n_+} \langle (\kappa_n/d) \rangle_{n/d}^{\text{new}} \mathcal{D}_d = \sum_{d \mid (n/\ell)_+} \langle (\kappa_n/(d\ell)) \rangle_{n/(d\ell)}^{\text{new}} \mathcal{D}_d = \langle \tilde{\kappa}_n/\ell \rangle_{n/\ell}^{\text{new}} = \tilde{\kappa}_{n/\ell}.$$

This completes the proof that  $\tilde{\kappa}$  is a Kolyvagin system.

Since  $\mathbf{KS}(F)$  is a free  $\mathbf{Z}_p$ -module of rank one [5, Theorem 5.2.10(ii)], to complete the proof it remains only to show that the map  $\mathbf{PKS}(F) \rightarrow \mathbf{KS}(F)$  is surjective. If  $\tilde{\kappa} \in \mathbf{KS}(F)$ , then (since  $\mathcal{D}_{n,1} = 1$ ) we can define inductively a collection  $\kappa := \{\kappa_n \in (\hat{F}^\times)^- \otimes I_n^r/I_n^{r+1} : n \in \mathcal{N}_p\}$  such that  $\sum_{d \mid n_+} \kappa_n/d \mathcal{D}_{n,d} = \tilde{\kappa}_n$  for every  $n$ . It is straightforward to check that  $\kappa$  is a pre-Kolyvagin system; since we will not make use of this, we omit the proof. By Definition 6.3 the image of  $\kappa$  in  $\mathbf{KS}(F)$  is  $\tilde{\kappa}$ .  $\square$

**COROLLARY 6.6.** *Suppose  $\kappa, \kappa' \in \mathbf{PKS}(F)$ . If  $\kappa_1 = \kappa'_1$ , then  $\kappa_n = \kappa'_n$  for every  $n \in \mathcal{N}_p$ .*

*Proof.* Let  $\tilde{\kappa}$  and  $\tilde{\kappa}'$  be the images of  $\kappa$  and  $\kappa'$ , respectively, under the map of Definition 6.3. Then  $\tilde{\kappa}$  and  $\tilde{\kappa}'$  are Kolyvagin systems, and  $\tilde{\kappa}_1 = \kappa_1 = \kappa'_1 = \tilde{\kappa}'_1$ . Therefore  $\tilde{\kappa} = \tilde{\kappa}'$  by Theorem 5.4, so by the injectivity assertion of Proposition 6.5 we have  $\kappa = \kappa'$ , i.e.,  $\kappa_n = \kappa'_n$  for every  $n \in \mathcal{N}_p$ .  $\square$

We will use the following definition and lemma to replace property (iv) in the definition of a pre-Kolyvagin system by an equivalent property that will be easier to verify. See Remark 6.9 below.

**DEFINITION 6.7.** If  $n \in \mathcal{N}$ , let  $\mathfrak{S}(n)$  denote the set of permutations of the primes dividing  $n_+$ , and let  $\mathfrak{S}_1(n) \subset \mathfrak{S}(n)$  be the subset

$$\mathfrak{S}_1(n) := \{\sigma \in \mathfrak{S}(n) : \text{the primes not fixed by } \sigma \text{ form a single } \sigma\text{-orbit}\}.$$

If  $\sigma \in \mathfrak{S}(n)$  let  $d_\sigma := \prod_{\ell \mid n_+, \sigma(\ell) \neq \ell} \ell$ , the product of the primes not fixed by  $\sigma$ , and define

$$\Pi(\sigma) := \prod_{q \mid d_\sigma} \pi_q(\text{Fr}_{\sigma(q)} - 1).$$

**LEMMA 6.8.** *Suppose that  $A$  is an abelian group,  $\ell$  is a prime that splits in  $F/\mathbf{Q}$ , and  $x_n \in A \otimes \mathcal{I}_n^{\text{new}}$  for every  $n \in \mathcal{N}_p$ . Then the following are equivalent:*

- (i) *For every  $n$  divisible by  $\ell$ ,  $\sum_{d \mid n_+} x_n/d \mathcal{D}_d = 0$ .*
- (ii) *For every  $n$  divisible by  $\ell$ ,  $x_n = - \sum_{\substack{\sigma \in \mathfrak{S}_1(n) \\ \sigma(\ell) \neq \ell}} \text{sign}(\sigma) x_n/d_\sigma \Pi(\sigma)$ .*

*Proof.* We show first that (ii) implies (i) (which is the implication we use later in this paper). Let  $\mathfrak{S}'(d) \subset \mathfrak{S}(d)$  denote the derangements, i.e., the permutations with no fixed points. Then we can evaluate the determinant  $\mathcal{D}_d = \det(M_d)$  as follows. Let  $m_{q,q'}$  be the  $(q, q')$ -entry in  $M_d$ . Then

$$\mathcal{D}_d = \sum_{\sigma \in \mathfrak{S}(d)} \text{sign}(\sigma) \prod_{q \mid d} m_{q, \sigma(q)} = \sum_{\sigma \in \mathfrak{S}'(d)} \text{sign}(\sigma) \Pi(\sigma), \quad (5)$$

where the second equality holds since the diagonal entries of  $M_d$  vanish.

Fix an  $n$  divisible by  $\ell$ , and let

$$S_1 = \sum_{d \mid n_+, \ell \nmid d} x_n/d \mathcal{D}_d, \quad S_2 = \sum_{d \mid n_+, \ell \mid d} x_n/d \mathcal{D}_d.$$

Using property (ii) we have

$$S_1 = - \sum_{\substack{d \mid n_+ \\ \ell \nmid d}} \sum_{\substack{\sigma \in \mathfrak{S}_1(n/d) \\ \sigma(\ell) \neq \ell}} \text{sign}(\sigma) \langle (x_n/(dd_\sigma))_\ell \rangle_{n/(dd_\sigma)}^{\text{new}} \Pi(\sigma) \mathcal{D}_d. \quad (6)$$

Fix a divisor  $\delta$  of  $n_+$  that is divisible by  $\ell$ . We will show that the coefficient of  $x_{n/\delta}$  in  $S_1$  in (6) is  $-\mathcal{D}_\delta$ , which exactly cancels the coefficient of  $x_{n/\delta}$  in  $S_2$ . Using (5), the coefficient of  $x_{n/\delta}$  in  $S_1$  in (6) is

$$- \sum_{d|\delta/\ell} \sum_{\substack{\sigma \in \mathfrak{S}_1(n/d) \\ d_\sigma = \delta/d}} \left( \text{sign}(\sigma) \Pi(\sigma) \sum_{\eta \in \mathfrak{S}'(d)} \text{sign}(\eta) \Pi(\eta) \right) = - \sum_{d|\delta/\ell} \sum_{\substack{\sigma \in \mathfrak{S}_1(n/d) \\ d_\sigma = \delta/d}} \sum_{\eta \in \mathfrak{S}'(d)} \text{sign}(\sigma\eta) \Pi(\sigma\eta).$$

For every  $\rho \in \mathfrak{S}'(\delta)$  there is a unique triple  $(d, \sigma, \eta)$  such that

$$d \mid \delta/\ell, \quad \sigma \in \mathfrak{S}_1(n/d), \quad d_\sigma = \delta/d, \quad \eta \in \mathfrak{S}'(d), \quad \text{and} \quad \rho = \sigma\eta.$$

To see this, simply write  $\rho$  as a product of disjoint cycles, let  $\sigma$  be the cycle containing  $\ell$ , and let  $d = \delta/d_\sigma$  and  $\eta = \sigma^{-1}\rho$ . Thus the coefficient of  $x_{n/\delta}$  in  $S_1$  in (6) is (using (5) again)

$$- \sum_{\rho \in \mathfrak{S}'(\delta)} \text{sign}(\rho) \Pi(\rho) = -\mathcal{D}_\delta.$$

Therefore  $\sum_{d|n_+} x_{n/d} \mathcal{D}_d = S_1 + S_2 = 0$ , so (i) holds.

Although we will not need it, here is a simple argument to show that (i) implies (ii). Suppose that  $X := \{x_n \in A \otimes \mathcal{I}_n^{\text{new}} : n \in \mathcal{N}_p\}$  satisfies (i). If  $\ell \mid n$ , then (since  $\mathcal{D}_1 = 1$ ) we can use (i) recursively to express  $x_n$  as a linear combination of  $x_d$  with  $\ell \nmid d$ . Thus  $X$  is uniquely determined by the subset  $X' := \{x_n \in A \otimes \mathcal{I}_n^{\text{new}} : n \in \mathcal{N}_p, \ell \nmid n\}$ . Clearly  $X'$  determines a unique collection  $Y := \{y_n \in A \otimes \mathcal{I}_n^{\text{new}} : n \in \mathcal{N}_p\}$  satisfying (ii), with  $y_n = x_n$  if  $\ell \nmid n$ . We showed above that (ii) implies (i), so  $Y$  satisfies (i). Since (i) and  $X'$  uniquely determine both  $X$  and  $Y$ , we must have  $X = Y$ , and so  $X$  satisfies (ii).  $\square$

REMARK 6.9. We will apply Lemma 6.8 as follows. Let  $A := (\hat{F}_{\ell, \text{f}}^\times)^-$ , and let  $x_n := \langle (\kappa_n)_{\ell, \text{f}} \rangle_n^{\text{new}}$ . Then Lemma 6.8 says that we can replace property (iv) in Definition 6.2 of a pre-Kolyvagin system by the equivalent statement:

$$(iv)' \text{ if } \ell \mid n_+, \text{ then } \langle (\kappa_n)_{\ell, \text{f}} \rangle_n^{\text{new}} = - \sum_{\substack{\sigma \in \mathfrak{S}_1(n) \\ \sigma(\ell) \neq \ell}} \text{sign}(\sigma) \langle (\kappa_{n/d_\sigma})_{\ell} \rangle_{n/d_\sigma}^{\text{new}} \Pi(\sigma).$$

## 7. The cyclotomic unit pre-Kolyvagin system

Fix an odd prime  $p$ . If  $n \in \mathcal{N}$ , let  $s(n)$  be the number of prime factors of  $n/n_+$ . In this section we will show that the collection  $\{2^{-s(n)} \tilde{\theta}'_n : n \in \mathcal{N}_p\}$  is a pre-Kolyvagin system. Recall that

$$\mathcal{N}_p^+ := \{n \in \mathcal{N}_p : \text{all } \ell \mid n \text{ split in } F/\mathbf{Q}\}.$$

PROPOSITION 7.1 (Darmon). *If  $n \in \mathcal{N}_p$  then*

$$\sum_{d|n_+} \tilde{\theta}'_{n/d} \prod_{\ell|d} \pi_{n/d}(\text{Fr}_\ell - 1) = 2^{s(n)} \beta_{n_+} \quad \text{in } (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$$

where for  $n \in \mathcal{N}_p^+$ ,  $\beta_n \in (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$  is the Kolyvagin derivative class denoted  $\kappa(n)$  in [1, §6], or  $\kappa_n$  in [6, Appendix].

*Proof.* This is Proposition 9.4 of [1].<sup>1</sup> (Note that  $\kappa(n)$  in [1, §6] and  $\kappa_n$  in [6, Appendix] are defined to lie in  $(\hat{F}^\times)^- \otimes (\mathbf{Z}/\gcd(\ell-1 : \ell|n)\mathbf{Z})$ , after fixing generators of every  $\Gamma_\ell$ . Without fixing such choices, the elements defined in [1] and [6] live naturally in  $(\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}.$ )  $\square$

<sup>1</sup>There is a typo in [1, Proposition 9.4]. The last two  $T$ 's should be  $TQ$ , as in [1, Lemma 8.1].

**THEOREM 7.2.** *The collection  $\{2^{-s(n)}\tilde{\theta}'_n : n \in \mathcal{N}_p\}$  is a pre-Kolyvagin system.*

*Proof.* We need to check the five properties of Definition 6.2. For  $n \in \mathcal{N}_p^+$ , let  $\beta_n$  be as in Proposition 7.1.

Since  $\beta_{n_+} \in (\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$  for every  $n$ , it follows easily by induction from Proposition 7.1 that  $\tilde{\theta}'_n \in (\hat{F}^\times)^- \otimes I_n^r/I_n^{r+1}$ , where  $r$  is the number of prime factors of  $n_+$ . This is property (i) of Definition 6.2.

Suppose  $\ell \mid n_+$ . A standard property of cyclotomic units shows that

$$\mathbf{N}_{F(\mu_n)/F(\mu_{n/\ell})}\alpha_n = \alpha_{n/\ell}/\alpha_{n/\ell}^{\text{Fr}_\ell^{-1}}.$$

It follows from the definition of  $\theta'_n$  that

$$\begin{aligned} (1 \otimes \pi_{n/\ell})(\theta'_n) &= \sum_{\gamma \in \Gamma_n} \gamma(\alpha_n) \otimes \pi_{n/\ell}(\gamma) = \sum_{\gamma \in \Gamma_{n/\ell}} \gamma(\mathbf{N}_{F(\mu_n)/F(\mu_{n/\ell})}\alpha_n) \otimes \gamma \\ &= \sum_{\gamma \in \Gamma_{n/\ell}} \gamma(\alpha_{n/\ell}/\alpha_{n/\ell}^{\text{Fr}_\ell^{-1}}) \otimes \gamma = \sum_{\gamma \in \Gamma_{n/\ell}} \gamma(\alpha_{n/\ell}) \otimes \gamma \pi_{n/\ell}(1 - \text{Fr}_\ell) = \theta'_{n/\ell} \pi_{n/\ell}(1 - \text{Fr}_\ell). \end{aligned}$$

Since  $\ell \mid n_+$  we have  $s(n) = s(n/\ell)$ , so this verifies property (ii) of Definition 6.2.

Projecting each of the summands in Proposition 7.1 into  $(\hat{F}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$ , one sees that all terms with  $d > 1$  vanish, yielding

$$\langle 2^{-s(n)}\tilde{\theta}'_n \rangle_n^{\text{new}} = \langle \beta_{n_+} \rangle_n^{\text{new}} = \beta_{n_+}.$$

Properties (iii), (iv), and (v) of Definition 6.2 follow from the corresponding properties of the  $\beta_{n_+}$ . See [5, Proposition A.2] or [9, Theorem 4.5.4] for (iii), and [5, Theorem A.4] or [6, Proposition A.2] for property (iv)' of Remark 6.9. Property (v) is immediate, since  $\beta_{n_+}$  depends only on  $n_+$ .  $\square$

## 8. The regulator pre-Kolyvagin system

In this section we study relations among the regulator elements  $R_n$ , to show that the collection  $\{h_n R_n : n \in \mathcal{N}_p\}$  is a pre-Kolyvagin system.

**LEMMA 8.1.** *Suppose  $n \in \mathcal{N}$ ,  $\ell \mid n_+$ , and  $\{\lambda_0 - \lambda_0^\tau, \dots, \lambda_r - \lambda_r^\tau\}$  is a standard basis of  $X_n^-$  with  $\lambda_r \lambda_r^\tau = \ell$ . Then  $\{\lambda_0 - \lambda_0^\tau, \dots, \lambda_{r-1} - \lambda_{r-1}^\tau\}$  is a standard basis of  $X_{n/\ell}^-$ , and we can choose an oriented basis  $\{\epsilon_0, \dots, \epsilon_r\}$  of  $(1 - \tau)\mathcal{E}_n$  such that  $\{\epsilon_0, \dots, \epsilon_{r-1}\}$  is an oriented basis of  $(1 - \tau)\mathcal{E}_{n/\ell}$ .*

*With any such bases,  $\text{ord}_{\lambda_r}(\epsilon_r) = -h_{n/\ell}/h_n$  and*

$$[\epsilon_r]_{\lambda_r}^{n/\ell} = \frac{h_{n/\ell}}{h_n} \pi_{n/\ell}(1 - \text{Fr}_\ell) \in I_{n/\ell}/I_{n/\ell}^2.$$

*Proof.* Everything except the final sentence is clear. Comparing the determinants of the logarithmic embeddings

$$(1 - \tau)\mathcal{E}_{n/\ell} \xrightarrow{\xi_{n/\ell}} X_{n/\ell}^-, \quad (1 - \tau)\mathcal{E}_n \xrightarrow{\xi_n} X_n^-$$

with respect to our given bases, we see that

$$\det(\xi_n) = \log |\epsilon_r|_{\lambda_r} \det(\xi_{n/\ell})$$

because  $\log |\epsilon_i|_{\lambda_r} = 0$  for  $0 \leq i < r$ . Since our bases are oriented, both determinants are positive. Hence

$$|\epsilon_r|_{\lambda_r} = \ell^{-\text{ord}_{\lambda_r}(\epsilon_r)} > 1$$

so  $\text{ord}_{\lambda_r}(\epsilon_r) < 0$ .

The exact sequence

$$(1 - \tau)\mathcal{E}_n \xrightarrow{\text{ord}_{\lambda_r}} \mathbf{Z} \xrightarrow{\cdot \lambda_r} \text{Pic}(\mathcal{O}_F[\ell/n]) \longrightarrow \text{Pic}(\mathcal{O}_F[1/n]) \longrightarrow 0$$

shows that

$$[\mathbf{Z} : \text{ord}_{\lambda_r}(\epsilon_r)\mathbf{Z}] = h_{n/\ell}/h_n,$$

so  $\text{ord}_{\lambda_r}(\epsilon_r) = -h_{n/\ell}/h_n$  as claimed. Since  $F(\mu_{n/\ell})/F$  is unramified at  $\lambda_r$ ,

$$[\epsilon_r]_{\lambda_r}^{n/\ell} = (\text{Fr}_\ell^{\text{ord}_{\lambda_r}(\epsilon_r)}) - 1 = \text{ord}_{\lambda_r}(\epsilon_r)(\text{Fr}_\ell - 1) = -h_{n/\ell}/h_n(\text{Fr}_\ell - 1)$$

in  $I_{n/\ell}/I_{n/\ell}^2$ . □

PROPOSITION 8.2. *Suppose  $n \in \mathcal{N}$ ,  $\ell \mid n_+$ , and  $r = r(n)$ . Then*

$$(1 \otimes \pi_{n/\ell})(h_n R_n) = h_{n/\ell} R_{n/\ell} \pi_{n/\ell}(1 - \text{Fr}_\ell) \in F^\times \otimes I_n^r/I_n^{r+1}.$$

*Proof.* To compute  $R_n$ , fix bases for  $X_n^-$  and  $\mathcal{E}_n^-$  as in Lemma 8.1. By definition

$$R_n := \begin{vmatrix} \epsilon_0 & \epsilon_1 & \cdots & \epsilon_r \\ [\epsilon_0]_{\lambda_1}^n & [\epsilon_1]_{\lambda_1}^n & \cdots & [\epsilon_r]_{\lambda_1}^n \\ \vdots & \vdots & & \vdots \\ [\epsilon_0]_{\lambda_r}^n & [\epsilon_1]_{\lambda_r}^n & \cdots & [\epsilon_r]_{\lambda_r}^n \end{vmatrix},$$

and then  $(1 \otimes \pi_{n/\ell})(R_n)$  is the determinant of the matrix obtained by applying  $\pi_{n/\ell}$  to rows 2 through  $r+1$  of this matrix. For  $i < r$ ,  $\epsilon_i$  is a unit at  $\lambda_r$ , so the local Artin symbol  $[\epsilon_i, F(\mu_n)_{\lambda_r}/F_{\lambda_r}]$  lies in the inertia group  $\Gamma_\ell$ . Hence  $\pi_{n/\ell}([\epsilon_i]_{\lambda_r}^n) = [\epsilon_i]_{\lambda_r}^{n/\ell} = 0$  for  $i < r$ , and so

$$(1 \otimes \pi_{n/\ell})(R_n) = \begin{vmatrix} \epsilon_0 & \cdots & \epsilon_{r-1} & \epsilon_r \\ [\epsilon_0]_{\lambda_1}^{n/\ell} & \cdots & [\epsilon_{r-1}]_{\lambda_1}^{n/\ell} & [\epsilon_r]_{\lambda_1}^{n/\ell} \\ \vdots & & \vdots & \vdots \\ [\epsilon_0]_{\lambda_{r-1}}^{n/\ell} & \cdots & [\epsilon_{r-1}]_{\lambda_{r-1}}^{n/\ell} & [\epsilon_r]_{\lambda_{r-1}}^{n/\ell} \\ 0 & \cdots & 0 & [\epsilon_r]_{\lambda_r}^{n/\ell} \end{vmatrix}.$$

The upper left  $r \times r$  determinant is the one used to define  $R_{n/\ell}$ , so

$$(1 \otimes \pi_{n/\ell})(R_n) = R_{n/\ell} [\epsilon_r]_{\lambda_r}^{n/\ell} = \frac{h_{n/\ell}}{h_n} R_{n/\ell} \pi_{n/\ell}(1 - \text{Fr}_\ell)$$

by Lemma 8.1. □

Fix an odd prime  $p$  as in §§5 and 6, and keep the rest of the notation of those sections as well.

LEMMA 8.3. *If  $n \in \mathcal{N}_p$ ,  $\ell$  is a prime not dividing  $n$ , and  $r = r(n)$ , then*

$$(R_n)_\ell \in (\hat{F}_{\ell, \text{f}}^\times)^- \otimes I_n^r/I_n^{r+1}.$$

*Proof.* Since  $\ell \nmid n$ , if  $\epsilon \in \mathcal{E}_n^-$  then  $\epsilon_\ell \in (\hat{\mathcal{O}}_\ell^\times)^- = (\hat{F}_{\ell, \text{f}}^\times)^- \subset (\hat{F}_\ell^\times)^-$ . Now the lemma is clear, since  $R_n \in \mathcal{E}_n^- \otimes I_n^r/I_n^{r+1}$ . □

PROPOSITION 8.4. *Suppose  $n \in \mathcal{N}_p$  and  $\ell \mid n_+$ . Then*

$$\langle h_n(R_n)_{\ell, \text{tr}} \rangle_n^{\text{new}} = (\phi_\ell^{\text{fs}} \otimes 1)(\langle h_{n/\ell}(R_{n/\ell})_\ell \rangle_{n/\ell}^{\text{new}}).$$

*Proof.* Note that  $(\phi_\ell^{\text{fs}} \otimes 1)(\langle h_{n/\ell}(R_{n/\ell})_\ell \rangle_{n/\ell}^{\text{new}}) \in (\hat{F}_{\ell, \text{tr}}^\times)^- \otimes \mathcal{I}_n^{\text{new}}$  is well-defined, since Lemma 8.3 shows that  $(R_{n/\ell})_\ell \in (\hat{F}_{\ell, \text{f}}^\times)^- \otimes I_{n/\ell}^{r-1}/I_{n/\ell}^r$ .

As in the proof of Proposition 8.2, fix a basis  $\{\lambda_0 - \lambda_0^\tau, \dots, \lambda_r - \lambda_r^\tau\}$  of  $X_n^-$  with  $\ell = \lambda_r \lambda_r^\tau$ , and an oriented basis  $\{\epsilon_0, \dots, \epsilon_r\}$  of  $(1 - \tau)\mathcal{E}_n$  as in Lemma 8.1. Then

$$(R_n)_{\ell, \text{tr}} = \begin{vmatrix} (\epsilon_0)_{\ell, \text{tr}} & \cdots & (\epsilon_{r-1})_{\ell, \text{tr}} & (\epsilon_r)_{\ell, \text{tr}} \\ [\epsilon_0]_{\lambda_1}^n & [\epsilon_1]_{\lambda_1}^n & \cdots & [\epsilon_r]_{\lambda_1}^n \\ \vdots & \vdots & & \vdots \\ [\epsilon_0]_{\lambda_r}^n & [\epsilon_1]_{\lambda_r}^n & \cdots & [\epsilon_r]_{\lambda_r}^n \end{vmatrix} = \text{ord}_{\lambda_r}(\epsilon_r) \begin{vmatrix} 1 & \cdots & 1 & (\ell, \ell^{-1}) \\ [\epsilon_0]_{\lambda_1}^n & [\epsilon_1]_{\lambda_1}^n & \cdots & [\epsilon_r]_{\lambda_1}^n \\ \vdots & \vdots & & \vdots \\ [\epsilon_0]_{\lambda_r}^n & [\epsilon_1]_{\lambda_r}^n & \cdots & [\epsilon_r]_{\lambda_r}^n \end{vmatrix}$$

since  $(\epsilon_r)_{\ell, \text{tr}} = (\ell, \ell^{-1})^{\text{ord}_{\lambda_r}(\epsilon_r)}$ , and  $(\epsilon_i)_{\ell, \text{tr}} = 1$  for  $i < r$ . (Recall that when we evaluate these determinants using (2), the multiplicative notation in  $(\hat{F}_\ell^\times)_{\text{tr}}$  changes to additive notation in the tensor product  $(\hat{F}_\ell^\times)_{\text{tr}} \otimes I_\ell^r / I_\ell^{r+1}$ , so 1's in the top row become 0's, and  $(\ell, \ell^{-1})^{\text{ord}_{\lambda_r}(\epsilon_r)}$  becomes  $\text{ord}_{\lambda_r}(\epsilon_r) \cdot (\ell, \ell^{-1})$ .) We have  $\text{ord}_{\lambda_r}(\epsilon_r) = -h_{n/\ell}/h_n$  by Lemma 8.1. For  $i < r$  we have  $\text{ord}_{\lambda_r}(\epsilon_i) = 0$ , so  $[\epsilon_i]_{\lambda_r}^n = [\epsilon_i]_{\lambda_r}^\ell \in I_\ell / I_\ell^2$  and

$$\phi_\ell^{\text{fs}}((\epsilon_i)_\ell) = (\ell, \ell^{-1}) \otimes [\epsilon_i]_{\lambda_r}^n \in (\hat{F}_\ell^\times)_{\text{tr}} \otimes I_\ell / I_\ell^2.$$

Thus

$$\begin{aligned} (R_n)_{\ell, \text{tr}} &= -\frac{h_{n/\ell}}{h_n} (-1)^r (-1)^{r-1} \begin{vmatrix} \phi_\ell^{\text{fs}}((\epsilon_0)_\ell) & \cdots & \phi_\ell^{\text{fs}}((\epsilon_{r-1})_\ell) \\ [\epsilon_0]_{\lambda_1}^n & \cdots & [\epsilon_{r-1}]_{\lambda_1}^n \\ \vdots & \vdots & \vdots \\ [\epsilon_0]_{\lambda_{r-1}}^n & \cdots & [\epsilon_{r-1}]_{\lambda_{r-1}}^n \end{vmatrix} \\ &= \frac{h_{n/\ell}}{h_n} \begin{vmatrix} \phi_\ell^{\text{fs}}((\epsilon_0)_\ell) & \cdots & \phi_\ell^{\text{fs}}((\epsilon_{r-1})_\ell) \\ [\epsilon_0]_{\lambda_1}^{n/\ell} + [\epsilon_0]_{\lambda_1}^\ell & \cdots & [\epsilon_{r-1}]_{\lambda_1}^{n/\ell} + [\epsilon_{r-1}]_{\lambda_1}^\ell \\ \vdots & \vdots & \vdots \\ [\epsilon_0]_{\lambda_{r-1}}^{n/\ell} + [\epsilon_0]_{\lambda_{r-1}}^\ell & \cdots & [\epsilon_{r-1}]_{\lambda_{r-1}}^{n/\ell} + [\epsilon_{r-1}]_{\lambda_{r-1}}^\ell \end{vmatrix} \end{aligned}$$

(the  $(-1)^r$  because we moved column  $r+1$  to column 1, and the  $(-1)^{r-1}$  because we moved row  $r+1$  to row 2). When we expand the last determinant (including expanding the sums  $[\epsilon_i]_{\lambda_j}^{n/\ell} + [\epsilon_i]_{\lambda_j}^\ell$ ), each term that includes one of the  $[\epsilon_i]_{\lambda_j}^\ell$  lies in  $I_\ell^2$  (since the top row also contributes one element of  $I_\ell$ ). Thus all such terms project to zero in  $\mathcal{I}_n^{\text{new}}$ , and so

$$\langle (R_n)_{\ell, \text{tr}} \rangle_n^{\text{new}} = \frac{h_{n/\ell}}{h_n} \langle \det(A) \rangle_n^{\text{new}}$$

where

$$A = \begin{bmatrix} \phi_\ell^{\text{fs}}((\epsilon_0)_\ell) & \cdots & \phi_\ell^{\text{fs}}((\epsilon_{r-1})_\ell) \\ [\epsilon_0]_{\lambda_1}^{n/\ell} & \cdots & [\epsilon_{r-1}]_{\lambda_1}^{n/\ell} \\ \vdots & \vdots & \vdots \\ [\epsilon_0]_{\lambda_{r-1}}^{n/\ell} & \cdots & [\epsilon_{r-1}]_{\lambda_{r-1}}^{n/\ell} \end{bmatrix}.$$

But then  $\det(A) = (\phi_\ell^{\text{fs}} \otimes 1)((R_n/\ell)_\ell)$ , so the proposition follows.  $\square$

Suppose  $n, n' \in \mathcal{N}$ ,  $n \mid n'$ , and  $r = r(n)$ . Define

$$S_{n, n'} := \begin{vmatrix} \epsilon_0 & \epsilon_1 & \cdots & \epsilon_r \\ [\epsilon_0]_{\lambda_1}^{n'} & [\epsilon_1]_{\lambda_1}^{n'} & \cdots & [\epsilon_r]_{\lambda_1}^{n'} \\ \vdots & \vdots & & \vdots \\ [\epsilon_0]_{\lambda_r}^{n'} & [\epsilon_1]_{\lambda_r}^{n'} & \cdots & [\epsilon_r]_{\lambda_r}^{n'} \end{vmatrix} \in \mathcal{E}_n^- \otimes I_{n'}^r / I_{n'}^{r+1},$$

using any standard basis of  $X_n^-$  and oriented basis of  $(1 - \tau)\mathcal{E}_n$ . In particular  $S_{n, n} = R_n$ .

PROPOSITION 8.5. Suppose  $n \in \mathcal{N}$  and  $\ell \nmid n$ .

(i) If  $\ell$  is inert in  $F/\mathbf{Q}$ , then  $h_{n\ell}\langle R_{n\ell}\rangle_n^{\text{new}} = h_n\langle R_n\rangle_n^{\text{new}}$ .

(ii) If  $\ell$  splits in  $F/\mathbf{Q}$  and  $v \in I_n$ , then

$$h_n\langle S_{n,n\ell}v\rangle_{n\ell}^{\text{new}} = \langle R_n\rangle_n^{\text{new}}\pi_\ell(v) - \sum_{\text{primes } q|n_+} h_{n/q}\langle S_{n/q,n}v\rangle_n^{\text{new}}\pi_\ell(\text{Fr}_q - 1)$$

in  $\mathcal{E}_n^- \otimes \mathcal{I}_{n\ell}^{\text{new}}$ .

*Proof.* Let  $r$  be the number of prime divisors of  $n_+$ , so  $X_n^-$  and  $(1-\tau)\mathcal{E}_n$  are free  $\mathbf{Z}$ -modules of rank  $r+1$ . Choose a standard basis of  $X_n^-$  and an oriented basis of  $(1-\tau)\mathcal{E}_n$ . For  $1 \leq i \leq r = r(n)$ , let

$$a_i = ([\epsilon_0]_{\lambda_i}^n, [\epsilon_1]_{\lambda_i}^n, \dots, [\epsilon_r]_{\lambda_i}^n), \quad b_i = ([\epsilon_0]_{\lambda_i}^\ell, [\epsilon_1]_{\lambda_i}^\ell, \dots, [\epsilon_r]_{\lambda_i}^\ell).$$

Then

$$S_{n,n\ell} = \begin{vmatrix} \epsilon_0 & \cdots & \epsilon_r \\ a_1 + b_1 & & \\ \vdots & & \\ a_r + b_r & & \end{vmatrix} = \sum_{T \subset \{1, \dots, r\}} \det(A_T) \quad (7)$$

where  $A_T$  is the matrix whose top row is  $(\epsilon_0, \dots, \epsilon_r)$  and whose  $(i+1)$ -st row for  $1 \leq i \leq r$  is  $b_i$  if  $i \in T$  and  $a_i$  if  $i \notin T$ . Note that  $\det(A_\emptyset) = R_n$ , and that the entries of each  $b_i$  are in  $I_\ell/I_\ell^2$ .

Suppose first that  $\ell$  is inert in  $F/\mathbf{Q}$ , so  $(n\ell)_+ = n_+$ . Then  $\langle \det(A_T) \rangle_n^{\text{new}} = 0$  if  $T$  is nonempty (since  $\mathcal{I}_n^{\text{new}}$  has no “ $\ell$  component”), so (7) shows that

$$\langle S_{n,n\ell} \rangle_n^{\text{new}} = \langle \det(A_\emptyset) \rangle_n^{\text{new}} = \langle R_n \rangle_n^{\text{new}}.$$

Further, since  $\ell$  is inert in  $F/\mathbf{Q}$  we have  $X_{n\ell}^- = X_n^-$ ,  $(1-\tau)\mathcal{E}_{n\ell} = (1-\tau)\mathcal{E}_n$ , and  $h_{n\ell} = h_n$ . Thus  $S_{n,n\ell} = R_{n\ell}$ , and so

$$h_{n\ell}\langle R_{n\ell} \rangle_{n\ell}^{\text{new}} = h_n\langle S_{n,n\ell} \rangle_n^{\text{new}} = h_n\langle R_n \rangle_n^{\text{new}}.$$

This is (i).

Now suppose that  $\ell$  splits in  $F/\mathbf{Q}$ . Since the entries of each  $b_i$  are in  $I_\ell$ , if  $\#(T) \geq 2$  we have  $\langle \det(A_T)v \rangle_{n\ell}^{\text{new}} = 0$ . Thus (7) gives

$$\langle S_{n,n\ell}v \rangle_{n\ell}^{\text{new}} = \langle \det(A_\emptyset)v \rangle_{n\ell}^{\text{new}} + \sum_{i=1}^r \langle \det(A_{\{i\}})v \rangle_{n\ell}^{\text{new}}. \quad (8)$$

By definition of  $R_n$ ,

$$\langle \det(A_\emptyset)v \rangle_{n\ell}^{\text{new}} = \langle R_n v \rangle_{n\ell}^{\text{new}} = \langle R_n \rangle_n^{\text{new}}\pi_\ell(v). \quad (9)$$

To compute  $\det(A_{\{i\}})$ , let  $q = \lambda_i\lambda_i^\tau$ , and assume that our oriented basis of  $(1-\tau)\mathcal{E}_n$  was chosen so that  $\{\epsilon_0, \dots, \epsilon_{r-1}\}$  is an oriented basis of  $(1-\tau)\mathcal{E}_{n/q}$  with respect to the standard basis of  $X_{n/q}$  obtained by removing  $\lambda_i - \lambda_i^\tau$  from  $\{\lambda_1 - \lambda_1^\tau, \dots, \lambda_r - \lambda_r^\tau\}$ . For  $1 \leq j \leq r-1$ ,  $\epsilon_j$  is a unit at  $\lambda_i$ , so

$[\epsilon_j]_{\lambda_i}^\ell = 0$ . Thus

$$\det(A_{\{i\}}) = \begin{vmatrix} \epsilon_0 & \cdots & \epsilon_{r-1} & \epsilon_r \\ [\epsilon_0]_{\lambda_1}^n & \cdots & [\epsilon_{r-1}]_{\lambda_1}^n & [\epsilon_r]_{\lambda_1}^n \\ \vdots & & \vdots & \vdots \\ 0 & \cdots & 0 & [\epsilon_r]_{\lambda_i}^\ell \\ \vdots & & \vdots & \vdots \\ [\epsilon_0]_{\lambda_r}^n & \cdots & [\epsilon_{r-1}]_{\lambda_r}^n & [\epsilon_r]_{\lambda_r}^n \end{vmatrix} = (-1)^{r+i} \begin{vmatrix} \epsilon_0 & \cdots & \epsilon_{r-1} \\ [\epsilon_0]_{\lambda_1}^n & \cdots & [\epsilon_{r-1}]_{\lambda_1}^n \\ \vdots & \vdots & \vdots \\ [\epsilon_0]_{\lambda_r}^n & \cdots & [\epsilon_{r-1}]_{\lambda_r}^n \end{vmatrix} [\epsilon_r]_{\lambda_i}^\ell$$

$$= (-1)^{r+i} S_{n/q,n} [\epsilon_r]_{\lambda_i}^\ell$$

(where the second determinant has no  $\lambda_i$  row). Further, an argument identical to that of Lemma 8.1 shows that

$$[\epsilon_r]_{\lambda_i}^\ell = (-1)^{r+i+1} \frac{h_{n/q}}{h_n} \pi_\ell(\text{Fr}_q - 1) \in I_\ell / I_\ell^2.$$

Therefore

$$\det(A_{\{i\}}) = -\frac{h_{n/q}}{h_n} S_{n/q,n} \pi_\ell(\text{Fr}_q - 1).$$

Multiplying (8) by  $h_n$  and using (9) gives

$$h_n \langle S_{n,n\ell} v \rangle_{n\ell}^{\text{new}} = h_n \langle R_n \rangle_n^{\text{new}} \pi_\ell(v) - \sum_{q|n_+} h_{n/q} \langle S_{n/q,n} v \pi_\ell(\text{Fr}_q - 1) \rangle_{n\ell}^{\text{new}}.$$

Since  $S_{n/q,n} \in I_n^r / I_n^{r+1}$ , we have

$$\langle S_{n/q,n} v \pi_\ell(\text{Fr}_q - 1) \rangle_{n\ell}^{\text{new}} = \langle S_{n/q,n} \pi_n(v) \rangle_n^{\text{new}} \pi_\ell(\text{Fr}_q - 1).$$

This completes the proof of the proposition.  $\square$

If  $n \in \mathcal{N}$ , recall (Definition 6.7) that  $\mathfrak{S}(n)$  denotes the set of permutations of the primes dividing  $n_+$ ,  $\mathfrak{S}_1(n) \subset \mathfrak{S}(n)$  is the subset

$$\mathfrak{S}_1(n) := \{\sigma \in \mathfrak{S}(n) : \text{the primes not fixed by } \sigma \text{ form a single } \sigma\text{-orbit}\},$$

and if  $\sigma \in \mathfrak{S}(n)$  then  $d_\sigma := \prod_{\sigma(\ell) \neq \ell} \ell$  and  $\Pi(\sigma) := \prod_{q|d_\sigma} \pi_q(\text{Fr}_{\sigma(q)} - 1)$ .

**THEOREM 8.6.** *If  $n \in \mathcal{N}_p$  and  $\ell \mid n_+$ , then*

$$\langle h_n(R_n)_{\ell,f} \rangle_n^{\text{new}} = - \sum_{\substack{\sigma \in \mathfrak{S}_1(n) \\ \sigma(\ell) \neq \ell}} \text{sign}(\sigma) \langle h_{n/d_\sigma}(R_{n/d_\sigma})_\ell \rangle_{n/d_\sigma}^{\text{new}} \Pi(\sigma).$$

*Proof.* As usual, fix a basis  $\{\lambda_0 - \lambda_0^\tau, \dots, \lambda_r - \lambda_r^\tau\}$  of  $X_n^-$  with  $\ell = \lambda_r \lambda_r^\tau$ , and an oriented basis  $\{\epsilon_0, \dots, \epsilon_r\}$  of  $(1 - \tau)\mathcal{E}_n$  as in Lemma 8.1, so that  $\{\epsilon_0, \dots, \epsilon_{r-1}\}$  is an oriented basis of  $(1 - \tau)\mathcal{E}_{n/\ell}$ . Then

$$(R_n)_{\ell,f} = \begin{vmatrix} (\epsilon_0)_{\ell,f} & \cdots & (\epsilon_{r-1})_{\ell,f} & (\epsilon_r)_{\ell,f} \\ [\epsilon_0]_{\lambda_1}^n & \cdots & [\epsilon_{r-1}]_{\lambda_1}^n & [\epsilon_r]_{\lambda_1}^n \\ \vdots & & \vdots & \vdots \\ [\epsilon_0]_{\lambda_r}^n & \cdots & [\epsilon_{r-1}]_{\lambda_r}^n & [\epsilon_r]_{\lambda_r}^n \end{vmatrix}.$$

For each  $i$ , we have  $[\epsilon_i]_{\lambda_r}^n = [\epsilon_i]_{\lambda_r}^{n/\ell} + [\epsilon_i]_{\lambda_r}^\ell$ . If  $i < r$ , then  $\epsilon_i$  is a unit at  $\lambda_r$  so  $[\epsilon_i]_{\lambda_r}^{n/\ell} = 0$ . Thus

$$(R_n)_{\ell,f} = \begin{vmatrix} (\epsilon_0)_{\ell,f} & \cdots & (\epsilon_r)_{\ell,f} \\ [\epsilon_0]_{\lambda_1}^n & \cdots & [\epsilon_r]_{\lambda_1}^n \\ \vdots & & \vdots \\ [\epsilon_0]_{\lambda_r}^\ell & \cdots & [\epsilon_r]_{\lambda_r}^\ell \end{vmatrix} + \begin{vmatrix} (\epsilon_0)_{\ell,f} & \cdots & (\epsilon_{r-1})_{\ell,f} & (\epsilon_r)_{\ell,f} \\ [\epsilon_0]_{\lambda_1}^n & \cdots & [\epsilon_{r-1}]_{\lambda_1}^n & [\epsilon_r]_{\lambda_1}^n \\ \vdots & & \vdots & \vdots \\ 0 & \cdots & 0 & [\epsilon_r]_{\lambda_r}^{n/\ell} \end{vmatrix}.$$



The map  $\epsilon \mapsto [\epsilon]_{\lambda_r}^\ell = [\epsilon, F_{\lambda_r}(\boldsymbol{\mu}_\ell)/F_{\lambda_r}] - 1$  is an isomorphism from  $(\hat{F}_{\ell, \text{f}}^\times)^- = (\hat{\mathcal{O}}_\ell^\times)^-$  to  $(I_\ell/I_\ell^2) \otimes \mathbf{Z}_p$ , and is zero on  $(\hat{F}_{\ell, \text{tr}}^\times)^-$  because  $\ell$  is a norm in the extension  $F_{\lambda_r}(\boldsymbol{\mu}_\ell)/F_{\lambda_r} = \mathbf{Q}_\ell(\boldsymbol{\mu}_\ell)/\mathbf{Q}_\ell$ . Hence the first determinant in the equation above is zero, because the top and bottom rows are linearly dependent. Also, if  $i < r$  then  $\epsilon_i$  is a unit at  $\lambda_r$ , so  $(\epsilon_i)_{\ell, \text{f}} = (\epsilon_i)_\ell$  and

$$(R_n)_{\ell, \text{f}} = \begin{vmatrix} (\epsilon_0)_\ell & \cdots & (\epsilon_{r-1})_\ell \\ [\epsilon_0]_{\lambda_1}^\ell & \cdots & [\epsilon_{r-1}]_{\lambda_1}^\ell \\ \vdots & & \vdots \\ [\epsilon_0]_{\lambda_{r-1}}^\ell & \cdots & [\epsilon_{r-1}]_{\lambda_{r-1}}^\ell \end{vmatrix} [\epsilon_r]_{\lambda_r}^{n/\ell} = (S_{n/\ell, n})_\ell [\epsilon_r]_{\lambda_r}^{n/\ell}.$$

By Lemma 8.1,  $[\epsilon_r]_{\lambda_r}^{n/\ell} = -(h_{n/\ell}/h_n) \pi_{n/\ell}(\text{Fr}_\ell - 1)$ . Thus

$$h_n \langle (R_n)_{\ell, \text{f}} \rangle_n^{\text{new}} = -h_{n/\ell} \langle (S_{n/\ell, n})_\ell \pi_{n/\ell}(\text{Fr}_\ell - 1) \rangle_n^{\text{new}}. \quad (10)$$

We can now “simplify” (10) by inductively expanding the right-hand side using Proposition 8.5. Specifically, expand  $\langle (S_{n/\ell, n} \pi_{n/\ell}(\text{Fr}_\ell - 1)) \rangle_n^{\text{new}}$  using Proposition 8.5(ii). Then expand each of the resulting  $\langle (S_{n/(\ell q), n/\ell} \pi_{n/(q\ell)}(\text{Fr}_q - 1)) \rangle_{n/\ell}^{\text{new}}$  using Proposition 8.5(ii) again. Continue until no terms  $S_{m/q, m}$  remain. The resulting sum consists of one term

$$(-1)^k \langle h_{n/(q_1 \cdots q_k)} (R_{n/(q_1 \cdots q_k)})_\ell \rangle_{n/(q_1 \cdots q_k)}^{\text{new}} \prod_{i=1}^k \pi_{q_i}(\text{Fr}_{q_{i+1}} - 1)$$

for each sequence  $q_1 = \ell, q_2, \dots, q_k$  of distinct primes dividing  $n_+$  (with  $q_{k+1} = \ell$ ). Identifying this sequence with the  $k$ -cycle  $\sigma := (\ell, q_2, \dots, q_k) \in \mathfrak{S}_1(n)$  gives the formula of the theorem, since  $\text{sign}(\sigma) = (-1)^{k-1}$ .  $\square$

**THEOREM 8.7.** *The collection  $\{h_n R_n : n \in \mathcal{N}_p\}$  is a pre-Kolyvagin system.*

*Proof.* We need to check the five properties of Definition 6.2. Property (i) is Lemma 8.3, (ii) is Proposition 8.2, (iii) is Proposition 8.4, (iv) is Theorem 8.6 along with of Remark 6.9, and (v) is Proposition 8.5(i).  $\square$

## 9. Proof of Theorem 3.9

*Proof of Theorem 3.9.* Fix an odd prime  $p$ . By Theorems 7.2 and 8.7, we have pre-Kolyvagin systems

$$\{2^{-s(n)} \tilde{\theta}_n : n \in \mathcal{N}_p\}, \quad \{-h_n R_n : n \in \mathcal{N}_p\}.$$

By Proposition 3.10,  $\tilde{\theta}'_1 = -h_1 R_1$  in  $\mathcal{O}_F^\times / \{\pm 1\}$ . Hence by Corollary 6.6,

$$2^{-s(n)} \tilde{\theta}_n = -h_n R_n \quad \text{in } (F^\times)^- \otimes \mathcal{I}_n^{\text{new}} \otimes \mathbf{Z}_p \text{ for every } n \in \mathcal{N}_p. \quad (11)$$

If  $p \mid n \in \mathcal{N}$ , then Proposition 4.2(iv) shows that  $(p-1)\mathcal{I}_n^{\text{new}} = 0$ . Therefore  $(F^\times)^- \otimes \mathcal{I}_n^{\text{new}} \otimes \mathbf{Z}_p = 0$  and (11) holds vacuously in this case. Since (11) holds for every  $n \in \mathcal{N}$  and every odd prime  $p$ , this completes the proof of Theorem 3.9.  $\square$

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