

## FACTORIZING HECKE POLYNOMIALS MODULO A PRIME

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Let  $T_{p,k}^{N,\chi}(x)$  be the characteristic polynomial of the Hecke operator  $T_p$  acting on the space of cusp forms  $S_k(N, \chi)$ . We describe the factorization of  $T_{p,k}^{N,\chi}(x) \bmod \ell$  as  $k$  varies, and we explicitly calculate those factorizations for  $N = 1$  and small  $\ell$ . These factorizations are used to deduce the irreducibility of certain  $T_{q,k}^{1,1}(x)$  from the irreducibility of  $T_{2,k}^{1,1}(x)$ .

### 1. Introduction and statement of results.

Let  $S_k(N, \chi)$  be the space of holomorphic cusp forms of integral weight  $k$  for the Hecke congruence subgroup  $\Gamma_0(N)$ , and denote by  $T_{p,k}^{N,\chi}(x)$  the characteristic polynomial of the Hecke operator  $T_p$  acting on  $S_k(N, \chi)$ . Let  $S_k(N) = S_k(N, 1)$  and set  $T_{p,k} = T_{p,k}^{1,1}$ . A conjecture of Maeda asserts that  $T_{p,k}(x)$  is irreducible and has full Galois group over  $\mathbb{Q}$ . This conjecture is related to the nonvanishing of  $L$ -functions [KZ], [CF], and to constructing base changes to totally real number fields for level 1 eigenforms, [HM]. Maeda's conjecture has been checked for all primes  $p < 2000$  and weights  $k \leq 2000$  [B], [CF], [FJ].

The methods which have been used to check Maeda's conjecture involve computing the factorization of  $T_{2,k}(x) \bmod \ell$  for various  $\ell$ . One searches for enough factorizations to deduce that  $T_{2,k}(x)$  is irreducible and has full Galois group over  $\mathbb{Q}$ . With a small amount of additional calculation it is possible to deduce the same conclusion for other  $T_{p,k}(x)$ . The method of translating information about  $T_{2,k}(x)$  to information about  $T_{p,k}(x)$  is related to the following result of James and Ono.

**Theorem ([JO]).** *Suppose  $q$  and  $\ell$  are distinct primes. Then*

$$\#\left\{\text{prime } p < X \mid T_{p,k}^{N,\chi}(x) \equiv T_{q,k}^{N,\chi}(x) \bmod \ell\right\} \gg X/\log X.$$

*In particular, if  $T_{p,k}^{N,\chi}(x)$  is irreducible mod  $\ell$  for some  $p$ , then the same holds for a positive proportion of primes  $p$ .*

The above result makes use of the Chebotarev density theorem and deep results of Deligne, Serre, and Shimura on the Galois representations associated to modular forms. In this paper we describe how to determine, with

a finite calculation, the factorization of  $T_{p,k}^{N,\chi}(x) \bmod \ell$  for any  $k$ . We use those factorizations to give an easy proof of the following result, which is similar to the second statement in the theorem given above.

**Theorem 1.** *If  $T_{n,k}(x)$  is irreducible and has full Galois group for some  $n$ , then  $T_{p,k}(x)$  is irreducible and has full Galois group for  $p$  prime and  $p \not\equiv \pm 1 \pmod{5}$ , or  $p \not\equiv \pm 1 \pmod{7}$ .*

Note that the conclusion of Theorem 1 holds for 5/6 of all primes  $p$ . Farmer and James [FJ] have used a version of the above result to show that  $T_{p,k}(x)$  is irreducible and has full Galois group if  $p < 2000$  and  $k \leq 2000$ .

In Section 2 we describe the factorizations of  $T_{p,k}^{N,\chi}(x) \bmod \ell$ . In Section 3 we give some examples. In Section 4 we deduce some corollaries and prove Theorem 1.

Throughout the paper,  $p$ ,  $q$ , and  $\ell$  are distinct rational primes;  $N$  and  $n$  are positive rational integers with  $N$ ,  $np$ ,  $q$ , and  $\ell$  pairwise coprime;  $k$  is a positive rational integer, and  $\chi$  is a character of conductor  $N$  with  $\chi(-1) = (-1)^k$ . We write  $T_{n,k}^{N,\chi}(x)$  for the characteristic polynomial of  $T_n$  acting on the space of cusp forms  $S_k(N, \chi)$  and put  $T_{n,k}(x) = T_{n,k}^{1,1}(x)$ . When we refer to the irreducibility or to the Galois group of a polynomial, we will mean over  $\mathbb{Q}$ . For prime  $p$  we write  $p^A || b$  to mean  $p^A | b$  and  $p^{A+1} \nmid b$ .

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## 2. Patterns in the factorization of $T_{p,k}^{N,\chi}(x) \bmod \ell$ .

Fix  $p$ ,  $\ell$ ,  $N$ , and  $\chi$ . In this section we describe the factorization of  $T_{p,k}^{N,\chi}(x) \bmod \ell$  as  $k$  varies. We show that those factorizations follow a pattern. In principle one can use this pattern to determine  $T_{p,k}^{N,\chi}(x) \bmod \ell$  for any  $k$ , after an initial calculation. In the following section we give some examples for  $N = 1$  and small  $\ell$ .

The idea here is to consider  $S_k(N, \chi) \bmod \ell$  and  $T_n \bmod \ell$ , and to find a basis  $B_k(N, \chi)$  of  $S_k(N, \chi)$  with the following nice property.

**Lemma 1.** *Let  $[T_n]_{k,N,\chi}$  be the matrix of  $T_n$  with respect to the basis  $B_k(N, \chi)$ . Then  $[T_n]_{k,N,\chi}$  is block upper-triangular and  $[T_n]_{k,N,\chi} \subset [T_n]_{k+\ell-1,N,\chi}$ , where the smaller matrix is a block in the upper left corner of the larger matrix. In particular,  $T_{n,k+\ell-1}^{N,\chi}(x) \equiv g(x) T_{n,k}^{N,\chi} \bmod \ell$  for some polynomial  $g(x)$ .*

*Proof.* We define the basis  $B_k(N, \chi)$  as follows. The classical congruence for the level 1 Eisenstein series  $E_{\ell-1} \equiv 1 \pmod{\ell}$  gives an inclusion  $S_k(N, \chi) \subset S_{k+\ell-1}(N, \chi) \bmod \ell$ , given by multiplication by  $E_{\ell-1}$ . Choose  $B_k(N, \chi)$  to respect this inclusion. The Hecke operator  $T_n \bmod \ell$  also respects this

inclusion because we have

$$(T_n f)(z) = \frac{1}{n} \sum_{ad=n} \chi(a) a^k \sum_{0 \leq b < d} f\left(\frac{az+b}{d}\right)$$

and  $a^k \equiv a^{k+\ell-1} \pmod{\ell}$ . This proves Lemma 1. □

By Lemma 1, there is a sequence of polynomials  $f_j \in (\mathbb{Z}/\ell\mathbb{Z})[x]$ , depending only on  $N, \chi, p, \ell$ , and  $(k \pmod{\ell-1})$ , so that

$$(2.1) \quad T_{p,k}^{N,\chi}(x) \equiv \prod_{j=1}^J f_j(x) \pmod{\ell}.$$

The following Proposition explains why it is easy to understand  $T_{p,k}^{N,\chi}(x) \pmod{\ell}$  for any  $k$ .

**Proposition 1.** *The sequence  $f_j$  in (2.1) is periodic.*

Thus, the calculation of  $T_{p,k}^{N,\chi}(x) \pmod{\ell}$  for any  $k$  reduces to a finite calculation. The periodicity of  $f_j$  follows from the isomorphism  $W_{k+\ell+1} = W_k[1]$ . Here  $W_k = \widetilde{M}_{k+\ell-1}/\widetilde{M}_k$ , with  $\widetilde{M}_k$  the  $\mathbb{F}_\ell$  vector space obtained by reducing  $M_k \pmod{\ell}$ . See [J]. We give a different proof based on the trace formula.

*Proof.* The degree of each  $f_j$  is bounded by

$$M = \max_k (\dim S_{k+\ell-1}(N, \chi) - \dim S_k(N, \chi)).$$

This is finite because  $\dim S_k(N, \chi)$  grows linearly as a function of  $k$ .

The polynomial  $f_j$  has at most  $M$  roots, and the coefficients of  $f_j$  are symmetric functions in those roots. These can be expressed as polynomials in the traces of  $T_p, T_p^2, \dots, T_p^M$ , which in turn can be expressed as polynomials in  $T_{p^j}$  with  $j \leq M$ . Thus, the coefficients of  $f_j$  are just polynomials in the traces of  $T_p, T_{p^2}, \dots, T_{p^M} \pmod{\ell}$ .

Let  $\sigma_k^{N,\chi}(T_n)$  denote the trace of  $T_n$  acting on  $S_k(N, \chi)$ . We need only show that  $\sigma_k^{N,\chi}(T_n) \pmod{\ell}$  is periodic as a function of  $k$ . This follows from the Eichler-Selberg trace formula. We state the trace formula in the following way, retaining only the features necessary for our proof. For details see [SV] or [C].

**Lemma 2** (The trace formula). *There are explicit algebraic numbers  $A, B_m$ , and  $C_d$ , depending only on  $N, n$ , and  $\chi$ , such that*

$$\sigma_k^{N,\chi}(T_n) = A n^{k/2} (k-1) \chi(\sqrt{n}) + \sum_{|m| \leq 2\sqrt{n}} B_m \frac{\eta_m^{k-1} - \bar{\eta}_m^{k-1}}{\eta_m - \bar{\eta}_m} + \sum_{\substack{d|n \\ 0 < d \leq \sqrt{n}}} C_d d^k,$$

where  $\eta_m = \frac{m + \sqrt{m^2 - 4n}}{2}$ . Furthermore, each of  $A, B_m$ , and  $C_d$  is integral modulo the rational prime  $\ell$  for  $\ell \geq 5$  and  $\ell \nmid nN$ .

Each term in Lemma 2 is periodic mod  $\ell$  as a function of  $k$ ; therefore so is  $\sigma_k^{N,\chi}(T_n)$ . One slight complication is that if  $n$  is a square mod  $\ell$  and  $\ell < 4n$ , then for some  $m$  we may have  $\eta_m - \bar{\eta}_m \equiv 0 \pmod{\ell^K}$  for  $K \geq 1$ . In this case choose  $L$  so that  $\eta_m^{k+L} \equiv \eta_m^k \pmod{\ell^{K+1}}$ . This proves Proposition 1.  $\square$

In many cases the period of  $f_j$  is too large to actually compute on available computers. However, for  $N = 1$  and  $\ell$  reasonably small, the computation is tractable. In the next section we give several examples, and in the following section we use those examples to deduce Theorem 1.

### 3. Some factorizations of level 1 Hecke polynomials.

We give some examples of the factorizations of Hecke polynomials mod  $\ell$  described in the previous section. The easiest examples to calculate are for  $N = 1$  and  $\ell \leq 7$  or  $\ell = 13$ . In those cases

$$\dim S_{k+\ell-1}(1, 1) \leq 1 + \dim S_k(1, 1),$$

so  $T_{p,k}(x) \pmod{\ell}$  factors completely and we only need the trace of  $T_p$  to determine each factor.

There is a further simplification for  $\ell \leq 7$  arising from the classification of cusp forms mod  $\ell$ . For normalized Hecke eigenforms  $f = \sum a_n q^n$  and  $g = \sum b_n q^n$ , write  $f \equiv g \pmod{\ell}$  to mean  $a_n \equiv b_n \pmod{\ell}$  for  $(n, \ell) = 1$ . For any particular  $\ell$ , there are only finitely many congruence classes of Hecke eigenforms mod  $\ell$ . These are given explicitly by Serre [Ser] for  $\ell \leq 23$ .

For  $\ell = 2$  we have  $a_p \equiv 0 \pmod{2}$ , so  $T_{p,k}(x) \equiv x^{d_k} \pmod{2}$  for all  $p \neq 2$ . For  $\ell = 3, 5$ , or  $7$ , we have  $a_p \equiv p^m + p^n \pmod{\ell}$  for  $p \neq \ell$ , where  $m$  and  $n$  depend only on  $\ell$  and the Hecke eigenform. Thus, if  $p \equiv q \pmod{\ell}$  then  $a_p \equiv a_q \pmod{\ell}$ , so  $T_{p,k}(x) \equiv T_{q,k}(x) \pmod{\ell}$  if  $p \equiv q \pmod{\ell}$ . For  $\ell \leq 7$  this reduces the determination of  $T_{p,k}(x) \pmod{\ell}$  for all  $p$  and  $k$  to the calculation of a few cases. The results of those calculations are presented in the following Theorem.

**Theorem 2a.** *For prime  $\ell \leq 7$  and  $p \neq \ell$ , the Hecke polynomial  $T_{p,k}(x)$  factors as*

$$T_{p,k}(x) \equiv \prod_{j=1}^{d_k} (x - a_j) \pmod{\ell}$$

where  $\{a_j\}$  is a periodic sequence depending only on  $p \pmod{\ell}$  and  $k \pmod{\ell - 1}$ . We have

$$T_{p,k}(x) \equiv \begin{cases} (x - 2)^{d_k} \pmod{3}, & \text{if } p \equiv 1 \pmod{3} \\ x^{d_k} \pmod{3} & \text{if } p \equiv 2 \pmod{3} \end{cases}.$$

For  $\ell = 5$  or  $7$  the results are summarized in the tables below. The rows are labeled by the smallest prime in each congruence class mod  $\ell$ , the columns

are labeled by the congruence class of  $k \pmod{\ell - 1}$ , and the table entry gives one period of the sequence  $\{a_j\}$ . The tables are sufficient to determine  $T_{p,k}(x) \pmod{\ell}$  for all  $p$  because if  $\ell \leq 7$  and  $p \equiv q \pmod{\ell}$  then  $T_{p,k}(x) \equiv T_{q,k}(x) \pmod{\ell}$ .

$\ell = 5$	0	2	$\ell = 7$	0	2	4
$p = 11$	(2)	(2)	$p = 29$	(2)	(2)	(2)
2	(1,4)	(2,3)	2	(4,5)	(1,3)	(6,2)
3	(2,3)	(1,4)	3	(0,1,0,6)	(0,3,0,4)	(5,0,2,0)
19	(0)	(0)	11	(1,3)	(4,5)	(6,2)
			5	(0,3,0,4)	(0,1,0,6)	(2,0,5,0)
			13	(0)	(0)	(0)

For  $\ell > 7$  there are no simple relationships between  $T_{p,k}$  and  $T_{q,k} \pmod{\ell}$ , so each  $T_{p,k} \pmod{\ell}$  must be calculated separately. We give an example mod 13.

**Theorem 2b.** We have a factorization  $T_{2,k}(x) \equiv \prod_{j=1}^{d_k} (x - a_j) \pmod{13}$ , where  $\{a_j\}$  is a sequence of period 14 depending only on  $k \pmod{12}$ . The first 14 terms of each sequence are given in the following table, where each row corresponds to a congruence class of  $k \pmod{12}$ .

$\ell = 13$	$(a_1 \dots a_{14})$
$k \equiv 0 \pmod{12}$	(2, 12, 9, 4, 1, 11, 5, 11, 1, 4, 9, 12, 2, 8)
2	(4, 11, 5, 8, 2, 9, 10, 9, 2, 8, 5, 11, 4, 3)
4	(8, 6, 8, 9, 10, 3, 4, 5, 7, 5, 4, 3, 10, 9)
6	(5, 3, 12, 3, 5, 7, 6, 8, 10, 1, 10, 8, 6, 7)
8	(1, 10, 6, 11, 6, 10, 1, 12, 3, 7, 2, 7, 3, 12)
10	(11, 2, 7, 12, 9, 12, 7, 2, 11, 6, 1, 4, 1, 6)

The calculations for Theorem 2 were done in Mathematica. The method was to find a basis for  $S_k(1)$  using  $\Delta$ ,  $E_4$ , and  $E_6$ , and then explicitly compute the action of the Hecke operator. Representative cases were checked using the trace formula.

The period of  $a_j$  given in Theorem 2 is shorter than might have been predicted from Lemma 2. If  $p$  is not a square mod  $\ell$  then  $(m^2 - 4p, \ell) = 1$  for all  $m$ , so Fermat's little theorem gives  $\eta_m^k \equiv \eta_m^{k+\ell^2-1} \pmod{\ell}$ , which implies  $\sigma_k(T_p) = \sigma_{k+\ell^2-1}(T_p) \pmod{\ell}$ . This implies that the  $a_j \pmod{\ell}$  has period at most  $(\ell^2 - 1)/12$ . This is the actual period given for those cases in Theorem 2a and Theorem 2b. If  $p$  is a square mod  $\ell$  then the period of  $\sigma_k(T_p)$  is much larger, leading to a larger upper-bound for the period of  $a_j$ . (The largest case we needed is  $p = 11$ ,  $m = 3$ ,  $\ell = 7$ , where we

have  $\eta_3^{295} \equiv \eta_3 \pmod{7^2}$ .) However, as can be seen in the examples, the period of  $a_j$  is actually smaller. J.-P. Serre has pointed out to us that the elementary result  $W_{k+p+1} = W_k[1]$  gives the indicated periodicity, and this can also be used to explain the various patterns which appear in the table in Theorem 2b.

#### 4. Proof of Theorem 1.

In this section we deduce some consequences of the factorizations given in Theorem 2 and we use those factorizations to prove Theorem 1.

**Corollary.** *Suppose for some  $n$  that  $T_{n,k}(x)$  is irreducible over  $\mathbb{Q}$ . Then  $T_{p,k}(x)$  is irreducible if either of the following holds:*

- (i)  $\dim S_k(1)$  is odd and  $p \not\equiv \pm 1 \pmod{5}$  or  $p \not\equiv \pm 1 \pmod{7}$ , or
- (ii)  $\dim S_k(1) \equiv 2 \pmod{4}$  and  $p \equiv 3$  or  $5 \pmod{7}$ .

Note that the Corollary applies to 1/2 of all pairs  $(k, p)$ . Both the Corollary and Theorem 1 follow from the factorizations in Theorem 2 and the following proposition.

**Proposition 2.** *Suppose  $T_{n,k}(x)$  is irreducible for some  $n$ . Then for each  $m$  we have  $T_{m,k}(x) = f(x)^r$  with  $f(x)$  irreducible and  $r \in \mathbb{N}$ . Suppose  $T_{n,k}(x)$  is irreducible and has full Galois group for some  $n$ . Then for each  $m$  either  $T_{m,k}(x)$  is irreducible and has full Galois group, or  $T_{m,k}(x) = (x - a)^{d_k}$  for some  $a \in \mathbb{Z}$ .*

*Proof of the Corollary and Theorem 1.* If  $T_{p,k}(x) = f(x)^r$  then each root of  $T_{p,k}(x) \pmod{\ell}$  has multiplicity divisible by  $r$ . Using  $\ell = 5$  or  $7$  and the factorizations in Theorem 2a gives  $r = 1$  for all cases covered by the Corollary.

If  $T_{p,k}(x) = (x - a)^r$  then  $T_{p,k}(x)$  has only one root mod  $\ell$ . By Theorem 2a this does not hold in the cases covered by Theorem 1.  $\square$

*Sketch of Proof of Proposition 2.* The idea is to consider how the Galois group of the field of Fourier coefficients of the cusp forms acts on the Hecke basis.

Let  $B_k$  be the set of normalized Hecke eigenforms in  $S_k(1)$ , let  $\mathbb{K}_k/\mathbb{Q}$  be the field generated by the set of Fourier coefficients of the  $f \in B_k$ , and let  $G = \text{Gal}(\mathbb{K}_k/\mathbb{Q})$ . If  $f(z) = \sum a_n q^n$  with  $\{a_n\} \subset \mathbb{K}_k$  and  $\sigma \in G$  then set  $\sigma f(z) = \sum \sigma a_n q^n$ .

Since  $S_k(1)$  has a rational basis,  $G$  acts on  $S_k(1)$ . The group  $G$  also acts on the set  $B_k$  because  $G$  commutes with the Hecke operators. This induces an action on the roots of  $T_{n,k}(x)$  because those roots are the  $n$ th Fourier coefficients of the Hecke eigenforms. That action is the same as the natural action given by the inclusion of those roots in  $\mathbb{K}_k$ . Thus, if  $G$  acts transitively on  $B_k$  then  $G$  acts transitively on the roots of  $T_{m,k}(x)$ , which implies the first conclusion in the Proposition. If  $G$  acts as the full symmetric group on

$B_k$ , then  $G$  acts as the full symmetric group on the roots of  $T_{m,k}(x)$ , which implies the second conclusion in the Proposition.

To finish the proof, note that the Galois group of  $T_{n,k}(x)$  acts on  $B_k$  by extending the action on the  $n$ th Fourier coefficients. Thus, if  $T_{n,k}(x)$  is irreducible then  $\mathbb{K}_k$  is the splitting field of  $T_{n,k}(x)$  and  $G$  is its Galois group. This proves Proposition 2.  $\square$

It would be interesting to prove a version of Maeda's conjecture of the form "if  $T_{n,k}(x)$  is irreducible for some  $n$ , then it is irreducible for all  $n$ ," or even "if  $T_{n,k}(x)$  is irreducible for some  $n$ , then  $T_{2,k}(x)$  is irreducible." The methods used here are only able to establish such a result for a large proportion of weights  $k$ . By combining Theorem 2b with the Corollary above, we have that if  $T_{n,k}(x)$  is irreducible for some  $n$  and  $\dim S_k(1)$  is not a multiple of 14, then  $T_{2,k}(x)$  is irreducible, and if  $\dim S_k(1)$  is not a multiple of 28, then  $T_{2,k}(x)$  or  $T_{3,k}(x)$  is irreducible. Establishing factorizations of  $T_{2,k}(x) \pmod{\ell}$  for larger  $\ell$  would increase the proportion of  $k$  for which such a result is known. This is reminiscent of Lehmer's conjecture that the Ramanujan  $\tau$ -function never vanishes, where the results in that direction come from congruence properties of  $\tau(n)$ .

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