Computational aspects of modular parametrizations of elliptic curves

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Abstract

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Abstract goes here.

TABLE OF CONTENTS

GLOSSARY

ARGUMENT: replacement text which customizes a LaTeX macro for each particular usage.

DEDICATION

to all of you

Chapter 1

INTRODUCTION

Chapter 2

COMPUTING THE MAZUR SWINNERTON-DYER CRITICAL SUBGROUP OF ELLIPTIC CURVES

Chapter 3

CHOW-HEEGNER POINTS COMPUTATIONS

Chapter 4

FOURIER EXPANSIONS OF MODULAR FORMS FORMS AT ALL CUSPS

Let k be a positive even integer and let $f \in S_k(\Gamma_0(N))$ be a nonzero cusp form. Then f has a Fourier expansion at the cusp infinity:

$$f = \sum_{n \geq 1} a_n q^n$$

where a_n are complex numbers and $q = e^{2\pi i \tau}$. We are concerned with the problem of computing the Fourier expansion of f at other cusps. When N is square-free, this problem is solved by Asai [fixme: give reference]. The problem is studied in the Ph.D. thesis of Christophe Delaunay and in [Edixhoven], where a numerical algorithm is proposed. We will give a numerical algorithm to compute such expansions. Our approach is different from the one proposed in [Ed], for they require working at a higher level: to compute expansions at cusps of denominator Q, one needs to compute period matrices for forms of level NR^2, where $R = \gcd(Q, \frac{N}{Q})$. As a contrast, our algorithm works at levels dividing N.

The main results of this chapter are Theorem 4.6.7 and Algorithm 3, which gives a formula for the Fourier expansion of a newform $f \in S_k(\Gamma_0(N))$ at any cusp z of width one. Along the way, we have developed algorithms to compute the twists $f \otimes \chi$ and the pseudo-eigenvalue of newforms under the Fricke involution. Section contains some examples.

4.1 Preliminaries

Let $N \geq 1$ be an integer and let $X_0(N)$ be the modular curve of level N.

Definition 4.1.1. Let z be a cusp on $X_0(N)$. If $z \neq \infty$, write $z = [a/c]$ with $\gcd(a, c) = 1$.

The *denominator* of z is

$$d_z = \gcd(c, N).$$

. If $z = \infty$, we set $d_\infty = N$. Choose $\alpha \in SL_2(\mathbb{Z})$ such that $\alpha(\infty) = z$. The *width* of z is

$$h_z = \left| \frac{SL_2(\mathbb{Z})_\infty}{(\alpha^{-1}\{\pm I\}\Gamma_0(N)\alpha)_\infty} \right|$$

where the subscript ∞ means taking the isotropy subgroup of ∞ in the corresponding group.

The width of a cusp can be computed in terms of its denominator. In fact, we have

Lemma 4.1.2. *If z is a cusp on $X_0(N)$, then*

$$h_z = \frac{N}{\gcd(d_z^2, N)}.$$

Proof. When $z = [\infty]$, we have $d_\infty = N$ and $h_\infty = 1$, so the formula holds trivially. Otherwise, write $z = [\frac{a}{c}]$ and find $\alpha = \left(\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right) \in SL_2(\mathbb{Z})$. For $N' \in \mathbb{Z}$ we compute

$$\alpha \left(\begin{smallmatrix} 1 & N' \\ 0 & 1 \end{smallmatrix}\right) \alpha^{-1} = \left(\begin{smallmatrix} * & * \\ -c^2N' & * \end{smallmatrix}\right).$$

Hence $\left(\begin{smallmatrix} 1 & N' \\ 0 & 1 \end{smallmatrix}\right) \in (\alpha^{-1}\{\pm I\}\Gamma_0(N)\alpha)_\infty \iff N \mid c^2N' \iff \frac{N}{\gcd(d_z^2, N)} \mid N'$. This completes the proof. $\square$

In particular, the width of a cusp z is one if and only if $N \mid d_z^2$.

Suppose f is a modular form on $\Gamma_0(N)$ of positive even weight k and $\alpha \in GL_2(\mathbb{Q})$. Recall the weight-$k$ action is defined as

$$f|\alpha(z) = (\det(\alpha))^{k/2}(cz + d)^{-k} f(\alpha z),\ \alpha = \left(\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right).$$

In particular, if $\alpha \in SL_2(\mathbb{Z})$, then $f|\alpha$ is a modular form on $\Gamma(N)$. So $f|\alpha$ has a q-expansion, which is a power series in $q^{\frac{1}{N}}$. A natural thing to do is to define the expansion of f at the cusp z as the expansion of $f|\alpha$. However, note that this may not be well-defined: in general the expansion depends on the choice of α. Nonetheless, when the cusp z has width one, the expansion is indeed well-defined as a power series in q.

Lemma 4.1.3. *Let z be a cusp on $X_0(N)$ with $h_z = 1$. Choose $\alpha \in SL_2(\mathbb{Z})$ such that $\alpha(\infty) = z$. Then $f|\alpha$ is a cusp form on $\Gamma_1(N)$. Moreover, the function $f|\alpha$ is independent of the choice of α.*

Proof. It is easy to verify that $\Gamma_1(N) \subseteq \alpha^{-1}\Gamma_0(N)\alpha$, hence the first claim holds. Now suppose $\beta \in SL_2(\mathbb{Z})$ is such that $\beta(\infty) = z$. Then $\alpha^{-1}\beta \in SL_2(\mathbb{Z})_\infty$. Since z has width one, we have $\alpha^{-1}\beta \in \alpha^{-1}\Gamma_0(N)\alpha$. Hence $\beta \in \Gamma_0(N)\alpha$, and it follows that $f|[\beta] = f|[\alpha]$. $\square$

In light of the lemma above, we define the *q-expansion of f at a width one cusp z* to be the q-expansion of $f|[\alpha]$, and denote it by f_z.

Assume further that f is an eigenform under the Atkin-Lehner operators. We will show that in order to compute the expansion of $f|[\alpha]$ for any $\alpha \in SL_2(\mathbb{Z})$, it suffices to do so for $\alpha = \left(\begin{smallmatrix} 1 & 0 \\ m & 1 \end{smallmatrix}\right)$, where $0 \leq m < N$ and $N \mid \gcd(m, N)^2$. In particular, it suffices to compute the expansions of f at a some cusps of width one.

Lemma 4.1.4. *For any $\alpha \in SL_2(\mathbb{Z})$, there exists a matrix $w_Q \in W_N$ and an upper triangular matrix $u \in GL_2(\mathbb{Q})$ such that $w\alpha = \alpha' u$, where $\alpha' = \left(\begin{smallmatrix} a' & b \\ c' & d' \end{smallmatrix}\right) \in SL_2(\mathbb{Z})$ satisfies $N \mid \gcd(N, c')^2$.*

Indeed, one may find Q using Lemma. Now $f|[\alpha] = f|[w_Q][w_Q\alpha] = f|[w_Q][\alpha'][u] = \lambda_Q(f) f[\alpha'][u] = \lambda_Q(f) f[\alpha''][u]$, where α'' is of form $\left(\begin{smallmatrix} 1 & 0 \\ m & 1 \end{smallmatrix}\right)$. Note that for an upper triangular matrix $u = \left(\begin{smallmatrix} u_0 & u_1 \\ 0 & u_2 \end{smallmatrix}\right)$, we have $f[u](q) = f(q^{u_0/u_2} e^{2\pi i u_1/u_2})$.

4.2 Reducing to the case of newforms

The space $S_k(\Gamma_0(N))$ is spanned by elements of form $g(q^d)$, where g is newform of level $M \mid N$ and d is a divisor of $\frac{N}{M}$. Note that $g(q^d) = d^{-k/2} g|\left(\begin{smallmatrix} d & 0 \\ 0 & 1 \end{smallmatrix}\right)$. For any $\alpha \in SL_2(\mathbb{Z})$, we can find $\alpha' \in SL_2(\mathbb{Z})$ and $u \in GL_2(\mathbb{Q})$ such that $\left(\begin{smallmatrix} d & 0 \\ 0 & 1 \end{smallmatrix}\right)\alpha = \alpha' u$. Hence to compute all expansions $f|[\alpha]$, it suffices to give an algorithm for newforms.

In the rest of this chapter, we will restrict ourselves to solving the following problem:

Problem 4.2.1. Let f be a normalized newform in $S_k(\Gamma_0(N))$ and z be a cusp on $X_0(N)$ of width one. Compute the q-expansion of f_z.

4.3 Twists of newforms

For $f \in S_k(\Gamma_1(N), \epsilon)$ a newform with expansion $f = \sum_n a_n(f)q^n$ and χ a Dirichlet character, the *twist* f_χ is a modular form with expansion $f_\chi(q) = \sum a_n(f)\chi(n)q^n$.

Lemma 4.3.1. *[AWL78, Proposition 3.1] Let $F \in S_k(\Gamma_1(N), \epsilon)$, where ϵ is a character of conductor N'. Let χ be a character modulo M. Put $\tilde{N} = lcm N, N'M, M^2$. Then $F_\chi \in S_k(\Gamma_1(\tilde{N}), \epsilon\chi^2)$.*

In particular, when ϵ is the trivial character and the conductor M of χ satisfies $M^2 \mid N$, we have $F_\chi \in S_k(\Gamma_1(N), \chi^2))$.

We write $f \otimes \chi$ for the unique newform such that $a_p(f \otimes \chi) = a_p(f_\chi)$ for all but finitely many primes p. From now, we refer to $f \otimes \chi$ as *the twist of f by χ*.

We quote two more results from [AWL78], which we will use extensively. First, we recall the definitions of U_d and B_d operators. For a modular form $f = \sum a_n q^n$ and a positive integer d, we put

$$f|U_d = \sum a_{nd}q^n, \ f|B_d = \sum a_n q^{nd}.$$

Lemma 4.3.2. *[AWL78, Theorem 3.1] Let $q \mid N$ and Q be the q-primary part of N. Write $N = QM$. Let F be a newform in $S_k(\Gamma_1(N), \epsilon)$ with $\mathrm{cond}(\epsilon_Q) = q^\alpha, \alpha \geq 0$. Let χ be a character with conductor q^β, $\beta \geq 1$. Put $Q' = \max\{Q, q^{\alpha+\beta}, q^{2\beta}\}$. Then*
(1) For each prime $q' \mid M, F_\chi$ is not of level $Q'M/q$.
(2) The exact level of F_χ is $Q'M$ provided (a) $\max\{q^{\alpha+\beta}, q^{2\beta}\} < Q$ if $Q' = Q$, or (b) $\mathrm{cond}(\epsilon_Q\chi) = \max\{q^\alpha, q^\beta\}$ if $Q' > Q$.

Lemma 4.3.3. *[AWL78, Theorem 3.2] Let $q \mid N$ and Q be the q-primary part of N. Write $N = QM$. Let χ be a character with conductor equal a power of q. Let F be a newform in $S_k(\Gamma_1(N), \epsilon)$. Then $f \otimes \chi$ is a newform in $S_k(\Gamma_1(Q'M, \epsilon\chi^2)$, where Q' is a power of q, such that*

$$F_\chi = f \otimes \chi - (f \otimes \chi)|U_q|B_q.$$

Since our goal is to compute expansions of newforms on $\Gamma_0(N)$, we will make the following assumptions: from now, unless otherwise noted, we assume f has trivial character, and that $\mathrm{cond}(\chi)^2 \mid N$.

Next, we consider the problem of identifying the newform $f \otimes \chi$. This includes finding its level, which we denote by M_χ, and its q-expansion to arbitrarily many terms. We will assume that we have an oracle which, given weight k and level N, computes the expansions of all newforms in $S_k(\Gamma_1(N))$ to arbitrarily many terms (for example, use the algorithm in [Steb]).

Now we proceed on how to recognise the level of $f \otimes \chi$ from the coefficients of f. One potential obstacle is that we do not know all Fourier coefficients of $f \otimes \chi$. We only know that $a_n(f \otimes \chi) = a_n(f)\chi(n)$ when $\gcd(n, N) = 1$. This can be overcome using a variant of Sturm's argument. First we prove a lemma.

Lemma 4.3.4. *Let $f \in S_k(N, \epsilon)$ be a normalized newform. Then $f|U_q|B_q \in S_k(Nq^2, \epsilon)$.*

Proof. We use a standard fact that for any integer $d \geq 1$, the map $f \mapsto f|B_d$ takes $S_k(N, \epsilon)$ to $S_k(Nd, \epsilon)$. To prove the lemma, we consider two separate cases. First, assume $q \nmid N$, then we have $T_q = U_q + q^{k-1}\epsilon(q)B_q$. By our assumption, we have $f|T_q = a_q(f)f$. Therefore, we have $f|U_q|B_q = f|(T_q - q^{k-1}\epsilon(q)B_q)|B_q = a_q(f)f|B_q - q^{k-1}\epsilon(q)f|B_q^2$. Hence $f|U_q|B_q \in S_k(Nq^2, \epsilon)$. Now assume $q \mid N$, so $U_q = T_q$. Hence $f|U_q|B_q = a_q(f)f|B_q \in S_k(Nq, \epsilon) \subseteq S_k(Nq^2, \epsilon)$. $\square$

The next proposition generalised the usual Sturm bound argument for modular forms.

Proposition 4.3.5. *Let g_1, g_2 be two normalised newforms of levels $N_1 \mid N_2$ and the same nybentypus character ϵ. Assume ϵ has prime power conductor $Q = q^\beta$ such that $Q^2 \mid N$. Let B be the Sturm bound for the congruence subgroup $\Gamma_1(Nq^2)$. Suppose*

$$a_n(g_1) = a_n(g_2), \text{ for all } 1 \leq n \leq B \text{ such that } \gcd(n, q) = 1.$$

Then $g_1 = g_2$.

Proof. Following [AWL78], we define the operator K_q on the space of modular forms by

$$g|K_q = g - g|U_q|B_q.$$

Then the assumption is equivalent to the statement that $\delta = (g_1 - g_2)|K_q$ has $a_n(\delta) = 0$ for all $1 \leq n \leq B$. Since $\delta \in S_k(Nq^2, \epsilon)$, Sturm's theorem implies $\delta = 0$.

We know from [DS06, Theorem 5.7.1] that $g_1 - g_2 \in S_k(N_2, \epsilon)^{old}$. Suppose $N_1 < N_2$, then g_1 is in the old subspace, hence so is g_2, a contradiction. Therefore we must have $N_1 = N_2$. It follows that $g_1 - g_2 \in S_k(N_2, \epsilon)^{new}$, since g_1, g_2 are newforms. This forces $g_1 - g_2 = 0$. $\square$

Now we are ready to describe the algorithm.

Algorithm 1 Identifying $f \otimes \chi$

Input: k – a positive even integer; $f \in S_k(\Gamma_0(N))$ a normalized newform; χ a Dirichlet character of prime power conductor $Q = q^\beta$; $Q^2 \mid N$; B – a positive integer

Output: The level M_χ of $f \otimes \chi$ and the Fourier expansion of $f \otimes \chi$ up to q^B.

if $Q = 1$ **then**
    return N.
end if
$Q' := \mathrm{cond}(\chi^2)$; $N_0 := \frac{N}{q^{v_q(N)}}$; $M_0 := Q' N_0$; $t := \frac{N}{M_0} \in \mathbb{Z}$.
for each positive divisor d of t **do**
    Set $V_d := S_k(M_0 d, \chi^2)$.
    Compute a basis of newforms $\{g_1^{(d)}, \cdots g_{s_d}^{(d)}\}$ of V_d.
    Set $B_d :=$ the Sturm bound for $\Gamma_1(M_0 d q^2)$.
    for $1 \leq j \leq s_d$ **do**
        if $a_n(g_i^{(d)}) = a_n(f)\chi(n)$ for all $1 \leq n \leq B_d, \gcd(n, q) = 1$ **then**
            return $M_0 d$.
        end if
    end for
end for

We give some sample computations applying the above algorithm.

Example 4.3.6. Let f be the normalised newform attached to the elliptic curve

$$E : y^2 + xy + y = x^3 - x - 2$$

of Cremona label **50a**. Then $f \otimes \chi$ is new of level 50 for all Dirichlet characters χ with modulus 5. In other words, f is 5-minimal.

As another example, we demonstrate a newform which is not p-minimal.

Example 4.3.7. Let f be the normalised newform attached to the elliptic curve

$$E : y^2 + xy = x^3 + x^2 - 25x - 111$$

of label **98a**. Let χ be the Dirichlet character modulo 7 defined by $\chi(3 \pmod 7) = -1$. We found that $f \otimes \chi$ is a newform of level 14, with q-expansion

$$(f \otimes \chi)(q) = q - q^2 - 2q^3 + q^4 + 2q^6 + q^7 - q^8 + q^9 - 2q^{12} - 4q^{13} - q^{14} + O(q^{15}).$$

4.4 Pseudo-eigenvalues

Let ϵ be a Dirichlet character modulo N and let f be a newform in $S_k(N, \epsilon)$. For any divisor Q of N with $\gcd(Q, \frac{N}{Q}) = 1$, there is an algebraic number $w_Q(f)$ of absolute value one and a newform g in $S_k(N, \overline{\epsilon_Q}\epsilon_{N/Q})$ such that

$$W_Q(f) = w_Q(f)g,$$

Definition 4.4.1. The number $w_Q(f)$ is called the *pseudo-eigenvalue* of W_Q on f. We write $w(f) = w_N(f)$.

For a power series $f = \sum_{n \geq 0} a_n q^n$, its complex conjugate, denoted by f^*, is

$$f^*(q) = \sum \overline{a_n} q^n.$$

From [AWL78] we have $W_N(f) = w(f)f^*$. In the rest of this section, we describe an algorithm to efficiently compute $w(f)$ numerically. For a positive even integer k, let $\mathbb{M}(k)$ denote the space of weight-k modular symbols defined in [Steb]. The space $\mathbb{M}(k)$ is a quotient of $\mathbb{Z}[X,Y]_{k-2} \otimes \mathbb{P}^1(\mathbb{Q})^2$, and $GL_2(\mathbb{Q})$ acts on $\mathbb{M}(k)$ via the following rule

$$g(P(X,Y) \otimes \{\alpha, \beta\}) = P(g^{-1}(X,Y)^T)\{g(\alpha), g(\beta)\}.$$

Most importantly, there is a pairing between $\mathbb{M}(k)$ and the space of modular forms of weight k, defined as

$$\langle f, P(X,Y) \otimes \{\alpha, \beta\}\rangle_k = \int_\alpha^\beta f(z)P(z,1)dz.$$

We will suppress the subscript k if its value is clear from context.

Lemma 4.4.2. *Let $M \in \mathbb{M}(k)$ and $f \in S_k(\Gamma_1(N))$. Then*

$$N^{\frac{k}{2}-1}\langle f|W_N, M\rangle = \langle f, W_N M\rangle.$$

Proof. See proof of [Steb, Proposition 8.17]. Note that the extra factor $N^{\frac{k}{2}-1}$ is due to the different constants involved in the definition of the weight-k action of $GL_2(\mathbb{Q})$ on modular forms. $\square$

The map

$$* : P(x,y)\{\alpha, \beta\} \mapsto P(-x,y)\{-\bar{\alpha}, -\bar{\beta}\}$$

defines the *star involution* on the space $\mathbb{M}(k)$. We have $\langle f^*, M\rangle = \overline{\langle f, M^*\rangle}$.

Lemma 4.4.3. *Let f be a normalised newform on $\Gamma_1(N)$ with positive even weight k and let $M \in \mathbb{M}(k)$ be such that $W_N(M) = N^{k/2-1}M^*$. Assume $\langle f, M\rangle \neq 0$. Then*

$$w(f) = \frac{\langle f, M\rangle}{\overline{\langle f, M\rangle}}.$$

Proof. Since $W_N^2(M) = N^{k-2}M$ for all $M \in \mathbb{M}(k)$, the assumption implies $W_N(M^*) = N^{k/2-1}M$. Now

$$\begin{aligned}
& N^{k/2-1}\langle f|W_N, M^*\rangle = \langle f, W_N(M^*)\rangle \\
\Longrightarrow\ & N^{k/2-1}w(f)\langle f^*, M^*\rangle = N^{k/2-1}\langle f, M\rangle \\
\Longrightarrow\ & w(f) = \frac{\langle f, M\rangle}{\langle f^*, M^*\rangle} \\
\Longrightarrow\ & w(f) = \frac{\langle f, M\rangle}{\overline{\langle f, M\rangle}}.
\end{aligned}$$

□

Suppose $\alpha, \beta \in \{z \in \mathbb{C} | Im(z) > 0, |z| = 1/\sqrt{N}\}$. Then it is easy to verify that $M = (xy)^{k/2-1} \otimes \{\alpha, \beta\}$ satisfies $W_N(M) = M^*$. Finally, we arrive at the algorithm to compute $w(f)$.

Algorithm 2 Computing the pseudo-eigenvalue of newforms.

Input: k – a positive even integer. $f \in S_k(\Gamma_1(N))$ a normalized newform.

Output: a numerical approximation of $w(f)$.

```
n_0 := 10, z_0 := i/√N. δ = 10^{-3}.
Randomly generate n_0 points {z_1, ···, z_{N_0}} ⊆ {z | 0 < Im(z) < 1/(2√N), |z| = 1/√N}.
for 1 ≤ i ≤ n_0 do
    compute the period integral c_i = ∫_{z_0}^{z_i} 2πi f(z) z^{(k-2)/2} dz.
    w_i ← c_i / c̄_i.
end for
if the standard deviation of w_1, ···, w_{n_0} is less than δ then
    w ← (1/n_0)(Σ_i w_i).
    return w.
else
    return FAIL.
end if
```

4.5 Formula for the Fourier expansion of f at width one cusps: Part 1

First we recall some notations from [AWL78].

Definition 4.5.1. For a positive integer c', let $S_c' = \begin{pmatrix} 1 & \frac{1}{c'} \\ 0 & 1 \end{pmatrix}$. If χ is a character modulo c', we define the operator on modular forms

$$f|R_\chi(c') = \sum_{u=0}^{c'-1} \bar{\chi}(u) f|S_{c'}^u.$$

Write R_χ in short for $R_\chi(\mathrm{cond}(\chi))$. Note that $f|R_\chi = g(\bar{\chi})f_\chi$. Conversely, if $(a, M) = 1$, we have

$$\phi(c')S_{c'}^u = \sum_{\chi:cond(\chi)|c'} \chi(u)R_\chi(c'). \tag{4.5.1}$$

For our convenience, we define a new set of operators, which are basically the conjugates of S_c' and $R_\chi(c')$ by W_N. Let $A_c' = \left(\begin{smallmatrix} 1 & 0 \\ c' & 1 \end{smallmatrix}\right)$. Then we have

Fact 4.5.2. $-N \cdot A_{N/c'}^{-1} = W_N S_{c'} W_N$

From now on, we assume c is a divisor of N and $c' = \frac{N}{c}$. Then

$$A_c^{-1} = W_N S_{c'} W_N.$$

Since $W_N^2 = id$ as operators, we have

$$A_c^{-u} = W_N S_{c'}^u W_N,\ \forall u \in \mathbb{Z}.$$

Parallel to the notion of $R_\chi(c')$, let $\Phi_\chi(c) = \sum_{u=0}^{c'-1} \bar{\chi}(u) A_c^{-u}$.Then $\Phi_\chi(c) = W_N R_\chi(c') W_N$. Similar to Formula 4.5.1, we have

$$\varphi(c')A_c^{-a} = \sum_{\mathrm{cond}(\chi)|c'} \chi(a)\Phi_\chi(c) = \sum_{\mathrm{cond}(\chi)|c'} \chi(a) W_N R_\chi(c') W_N. \tag{4.5.2}$$

Finally, applying Formula 4.5.2 to f, we arrive at

$$f_{[\frac{a}{c}]}(q) = \tfrac{1}{\varphi(c')} \textstyle\sum_{\mathrm{cond}(\chi)|c'} \chi(-a) f|W_N R_\chi(c') W_N. \tag{4.5.3}$$

$$= \tfrac{w(f)}{\varphi(c')} \textstyle\sum_{\mathrm{cond}(\chi)|c'} \chi(-a) f|R_\chi(c') W_N. \tag{4.5.4}$$

Now it left to compute the expansions of each $f|R_\chi(c')|W_N$ in the sum.

4.6 Formula for the Fourier expansion of f at width one cusps: Part 2

In this section, we describe how to compute the expansion of $f|R_\chi(c')|W_N$. First note the following identity between operators on $S_k(\Gamma_1(N), \epsilon)$:

$$T_p = U_p + \epsilon(p)p^{\frac{k}{2}}B_p.$$

We recall some notations and a result from [Del02], which states that $f|R_\chi(c')$ is a constant multiple of some twist $f_{\chi_{nt}}$.

Definition 4.6.1. [Del02, Definition III.2.4] For a Dirichlet character χ modulo $b = \prod_{j\in J} p_j^{\alpha_j}$. Let $r = |J|$. Decompose χ uniquely as $\chi = \chi_1 \cdots \chi_r$, where χ_i is a character modulo $p_j^{\alpha_j}$. We define $\mathrm{cond}'(\chi)$ multiplicatively, by putting

$$\mathrm{cond}'(\chi_j) = \begin{cases} \mathrm{cond}(\chi_j) & if\, \mathrm{cond}(\chi_j) > 1 \\ p_j & else \end{cases}$$

Also, if $I = \{j \in J : \chi_j$ is trivial character modulo $p_j^{\alpha_j}\}$, we put $tr = \prod_{j\in I} p_j^{\alpha_j}$ $nt = b/tr$, $\chi_{tr} = \prod_{j\in I} \chi_j$, and $\chi_{nt} = \chi/\chi_{tr}$. Then we set

$$g'(\chi) = (-1)^{|I|}\chi_{nt}(tr)g(\chi_{nt}).$$

Here $g(\chi)$ is the usual Gauss sum associated with χ.

Lemma 4.6.2. *[Del02, Prop 2.6] Let c' be such that $c'^2 \mid N$. For a Dirichlet character χ mod c', we have*

$$f|R_\chi(c') = \begin{cases} g'(\bar{\chi})f_{\chi_{nt}} & if\, \mathrm{cond}'(\chi) = c \\ 0 & else \end{cases}$$

Next, we compute $f_{\chi_{nt}}$ by the following: suppose $g = f \otimes \chi_{nt}$. Then

$$f_{\chi_{nt}} = \prod_{i=1}^{r} g|K_{p_i}.$$

Moreover, we have

$$K_p = 1 - U_pB_p = \begin{cases} 1 - (T_p - \chi_{nt}^2(p)p^{\frac{k}{2}}B_p)|B_p & p \nmid M \\ 1 - T_p|B_p & p \mid M \end{cases}.$$

Using the commutativity of T and B, we can write $f_{\chi_{nt}}$ in the form $\sum c_i g(q_i^d)$, where c_i and d_i are constants. To give a precise formula, we use the following notation. For a finite set S of integers, let $p(S) = \prod_{s \in S} s$ denote the product of all elements in S.

Theorem 4.6.3. *Let $S_\chi = \{p_1, \cdots, p_r\}$ be the set of prime divisors of* $\mathrm{cond}(\chi)$*. Let $\mathcal{B}_{\chi,M} = \{(S_1, S_2)|S_1, S_2 \subseteq S_\chi, S_1 \cap S_2 = \emptyset, \gcd(M, p(S_2)) = 1.\}$. Write $g_\chi = f \otimes \chi$. Then*

$$f_{\chi_{nt}} = \sum_{(S_1,S_2) \in B_{S,M}} a_{p(S_1)}(g_\chi)p(S_2)^{k/2}\chi_{nt}^2(p(S_2))g_\chi|B_{p(S_1)p(S_2)^2}.$$

Theorem 4.6.3 will be our starting point of computing the expansion of f at width one cusps. We will use it to compute $f_{\chi_{nt}}|W_N$. First we prove two lemmas.

Lemma 4.6.4. *Let f be a newform of even weight k on $\Gamma_1(M)$ and suppose d, N are positive integers such that $Md \mid N$. Then*

$$f|B_d|W_N = \left(\frac{N}{Md^2}\right)^{k/2} w_M(f)\overline{f|B_{\frac{N}{Md}}}.$$

where $w_M(f)$ is the pseudo-eigenvalue of f defined in previous sections.

Proof. Straightforward computation.

$$\begin{aligned} f|B_d|W_N &= d^{-k/2} f|\left(\begin{smallmatrix} d & 0 \\ 0 & 1 \end{smallmatrix}\right)\left(\begin{smallmatrix} 0 & -1 \\ N & 0 \end{smallmatrix}\right) \\ &= d^{-k/2} f|\left(\begin{smallmatrix} 0 & -1 \\ M & 0 \end{smallmatrix}\right)\left(\begin{smallmatrix} N/md & 0 \\ 0 & 1 \end{smallmatrix}\right)\left(\begin{smallmatrix} d & 0 \\ 0 & d \end{smallmatrix}\right) \\ &= \left(\frac{N}{Md^2}\right)^{k/2} f|W_M|B_{N/Md} \\ &= \left(\frac{N}{Md^2}\right)^{k/2} w_M(f)\bar{f}|B_{N/Md} \\ &= \left(\frac{N}{Md^2}\right)^{k/2} w_M(f)\overline{f|B_{N/Md}}. \end{aligned}$$

□

Before stating the second lemma, we quote another result in [Li75] on the coefficients of a newform at primes dividing the level.

Lemma 4.6.5. *[Li75, Theorem 3 (iii)] Let* $f = \sum_{n\geq 1} a_n(f)q^n$ *be a normalized newform in* $S_k(\Gamma_1(N), \epsilon)$*,* p *a prime dividing* N*. Then*
(1) If ϵ *is a character modulo* N/p *and* $p^2 \mid N$*, then* $a_p(f) = 0$*.*
(2) If ϵ *is a character modulo* N/p *and* $p^2 \nmid N$*, then* $a_p(f)^2 = \epsilon(p)p^{k-2}$*.*
(3) If ϵ *is not a character modulo* N/p*, then* $|a_p(f)| = p^{\frac{k-1}{2}}$*.*

Lemma 4.6.6. *Using notations in Theorem 4.6.3, and assume* $(S_1, S_2) \in \mathcal{B}_{S,M}$ *is such that* $a_{p(S_1)}(g_\chi) \neq 0$*. Then* $Mp(S_1)p(S_2)^2 \mid N$*.*

Proof. Let p be a prime divisor of $N' := Mp(S_1)p(S_2)^2$. If $p \nmid M$, then $\mathrm{ord}_p(N') \leq \mathrm{ord}_p(\mathrm{cond}(\chi)^2) \leq \mathrm{ord}_p(N)$. So we assume $p \mid M$, hence $p \nmid p(S_2)$. If $p \nmid p(S_1)$, then it follows from $M \mid N$; if $p \mid p(S_1)$, we want to show that $\mathrm{ord}_p(M) < \mathrm{ord}_p(N)$. Suppose not, then $\mathrm{ord}_p(M) = \mathrm{ord}_p(N) \geq 2\,\mathrm{ord}_p(\mathrm{cond}(\chi))$. Since $\mathrm{cond}(\chi^2) \leq \mathrm{cond}(\chi)$, we know χ^2 is a character modulo M/p. Applying Lemma 4.6.5 to the newform g_χ on level M, we see that $a_p(g_\chi) = 0$, hence $a_{p(S_1)}(g_\chi) = 0$ by multiplicativity. □

Applying Lemma 4.6.4 to Theorem 4.6.3, we finally arrive at

Theorem 4.6.7. *Let* $k \geq 2$ *be an even integer and let* f *be a normalized newform in* $S_k(\Gamma_0(N))$*. Suppose* $z = \frac{a}{c}$ *is a cusp on* $X_0(N)$ *with width one and denominator* d_z*. Let* $d' = \frac{N}{d_z}$*. Then the Fourier expansion of* f *at the cusp* z *is*

$$f_z(q) = \frac{w(f)}{\varphi(d')} \sum_{\chi:\mathrm{cond}'(\chi)=d'} \chi(-a)g'(\bar{\chi})w(f\otimes\chi)f^!_\chi(q).$$

Here

- $w(f)$ *and* $w(f\otimes\chi)$ *are the pseudo-eigenvalues of* W_N*.*

- $g'(\chi)$ *is the modified Gauss sum in .*

- cond$'$ *is the modified conductor of a Dirichlet character in.*

- $f^!_\chi$ *is as follows: let* M_χ *denote the level of* $f \otimes \chi$*. Then*

$$f^!_\chi = \sum_{(S_1,S_2)\in B_{S_{\chi_{nt}},M_\chi}} (-1)^{|S_1|} a_{p(S_1)}(f\otimes\chi)\left(\frac{N}{M_\chi p(S_1)^2 p(S_2)^3}\right)^{k/2} \chi(p(S_2))\overline{f\otimes\chi|B_{\frac{N}{M_\chi p(S_1)p(S_2)^2}}}.$$

where the notations are from .

This theorem gives us an algorithm to compute the expansion of f_z, which we describe below. But first, we take a closer look at what ingredients goes into the expansion. Given a newform $f \in S_k(\Gamma_0(N))$ and a width one cusp z of denominator c. We need to consider the twist of f by all Dirichlet characters of conductor dividing c. For each such character χ, we then need to determine the level M_χ and q-expansion of the newform $f \otimes \chi$, the latter boils down to knowing $a_p(f \otimes \chi)$ for all $p \mid \text{cond}(\chi)$. Then we need to compute the. Finally, we combine these information together and apply Throem 4.6.7 to compute f_z.

Algorithm 3 Computing Fourier coefficients of f at width one cusps

Input: $f \in S_k(\Gamma_0(N))$ a newform; a, c – coprime integers such that $N \mid c^2$; B – a positive integer.

Output: The first B Fourier coefficients of $f_z(q)$.

1: $c' \leftarrow N/c$. $X \leftarrow$ The set of all Dirichlet characters χ such that $\text{cond}'(\chi) = c'$.
2: compute $w(f)$ using Algorithm 2.
3: **for** χ in X **do**
4: Compute M_χ and the expansion of $g_\chi := f \otimes \chi$ to B terms, using Algorithm 1
5: Compute $g'(\bar{\chi})$.
6: Compute $w(g_\chi)$ using Algorithm 2.
7: **end for**
8: Apply Theorem 4.6.7 to compute f_z to B terms.

4.7 A Converse Theorem

Given the work in previous sections, it is a natural question then to ask whether the information on twists of f is uniquely determined by the expansion of f at width one cusps. The answer is yes, and the precise statement is in the following theorem.

Theorem 4.7.1. *Let f be a normalized newform in $S_k(\Gamma_0(N))$. Assume the eigenvalue $w_N(f)$ is known. Suppose c is a positive divisor of N such that $N \mid c^2$. Then the expansions of f_z, where z runs through all cusps of denominator c, uniquely determines the following: for each Dirichlet character χ of such that* $\mathrm{cond}'(\chi) = c'$*, the level M_χ, the pseudo-eigenvalue w_{M_χ} and the q-expansion of the newform $f \otimes \chi$.*

Proof. By plug in different a's. We can solve for t_χ. Consider the first nonzero term of t_χ. Suppose

$$t_\chi = u_\chi q^{v_\chi} + O(q^{v_\chi+1}),\ u_\chi \neq 0.$$

Assuming that χ has prime power conductor $p^\beta > 1$, we claim that

$$\left|\frac{v^{k/2}}{u}\right| = \begin{cases} p^{k/2} & if p \nmid M_\chi \\ p^{1/2} & if p \mid M_\chi \text{ and } a_p(g) \neq 0 \\ 1 & else \end{cases} \cdot$$

Proof of claim: the first and third case are easy to verify using Theorem 4.6.7. Now assume $p \mid M$ and $a_p(g_\chi) \neq 0$. By Lemma 4.6.5, we have $|a_p(g_\chi)| = p^{k/2-1/2}$ or $p^{k/2-1}$. However, $|a_p(g_\chi)| = p^{k/2-1}$ only if $p \mid\mid M_\chi$ and χ^2 is a character modulo M_χ/p. This means χ^2 is the trivial character. By Lemma 4.3.2, we compute the p-level of $f = g_\chi \otimes \bar{\chi}$: note that $\max p, p^{\alpha+\beta}, p^{2\beta} > p$, so (ii) applies and the p-level of f is equal to $\max(p^\alpha, p^\beta) = p^\beta$, i.e., $\mathrm{ord}_p(N) = \beta$. This is impossible since we have $p^{2\beta} = \mathrm{cond}(\chi)^2 \mid N$.

Therefore, we have $|a_p(g_\chi)| = p^{k/2-1/2}$ and the claim follows.

Since $k \geq 2$, we could determine which case we are in. Then we can read off M_χ and $w_M(g_\chi)$. For example, if we are in the second case, then the level can be computed via

$M_\chi = \frac{N}{v_\chi p}$. Now the N/M_χ's coefficient of t_χ is

$$\begin{aligned} a_{\frac{N}{M}}(t_\chi) &= w(g_\chi)(\tfrac{N}{M})^{k/2}(1 - |a_p(g_\chi)|^2\chi^2(p)p^{-k/2}) \\ &= w(g_\chi)(\tfrac{N}{M})^{k/2}(1 - p^{k/2-1}\chi^2(p)). \end{aligned}$$

This allows us to solve $w(g_\chi)$. Finally, we compute $a_p(g_\chi)$ by $a_p(g) = \frac{-u_\chi}{w(g_\chi)\chi^2(p)(\frac{N}{Mp})^{k/2}}$. The value $a_p(g)$ determines the expansion of g_χ. Recursively, we could solve for all pn-coefficients of g_χ, from which we deduce it complete q-expansion.

In the general case, we consider the following subsets of S_χ. Let $S_1^* = \{p \in S_\chi : p \mid M\}$, $S_2^* = S_\chi \setminus S_1^*$, and $\widetilde{S_1^*} = \{p \in S_1^* : a_p(g_\chi) \neq 0\}$.

It follows that the leading term of t_χ belongs to the summand corresponding to $(\widetilde{S_1^*}, S_2^*)$ in Theorem 4.6.7. Still writing the leading term as $u_\chi q^{v_\chi}$, we have

$$u_\chi = w(g_\chi)\chi^2(p(S_2))a_{p(\widetilde{S_1^*})}(g_\chi)p(\widetilde{S_1^*})^{-k}(p(S_2^*)^{-3k/2}\left(\frac{N}{M_\chi}\right)^{k/2}, v_\chi = \frac{N}{M_\chi p(\widetilde{S_1^*})p(S_2^*)^2}.$$

Similar to the prime power conductor case above, we have $|a_{p(\widetilde{S_1^*})}(g_\chi)| = p(\widetilde{S_1^*})^{k/2-1/2}$. So

$$|v_\chi^k u_\chi^{-2}| = p(\widetilde{S_1^*})p(S_2^*)^2. \tag{4.7.1}$$

Hence we can factor $|v_\chi^k u_\chi^{-2}|$ and obtain $p(\widetilde{S_1^*})$ and $p(S_2^*)$. Then M_χ can be solved using v_χ. Plug it back into u_χ, we obtain $a_{p(\widetilde{S_1^*})}w(g_\chi)$. Finally, for each $p \in \widetilde{S_1^*}$, the $v_\chi p$'s coefficient of t_χ allows us to compute $a_{p(\widetilde{S_1^*})/p}(g_\chi)w(g_\chi)$. These together determines $w(g_\chi)$ and $a_{p(\widetilde{S_1^*})}$. The other Fourier coefficients of g_χ can then be computed recursively. □

4.8 Fields of definitions

In the previous sections, we have described an algorithm to compute the Fourier coefficients of f_z. In fact, the Fourier coefficients are algebraic numbers. More precisely, if c is the denominator of z and $c' = N/c$, then $f_z(q) \in K_f(\zeta_{c'})[[q]]$. Here K_f is the number field generated by the Fourier coefficients of f (at the cusp ∞). Although this result is well-known, we include a proof for the reader's convenience.

Lemma 4.8.1. *Let c be a cusp of denominator d and let $d' = N/d$. Then*

$$\mathbb{Q}(\{a_n(f,c)\}) \subseteq \mathbb{Q}(\{a_n(f)\}, \zeta_{d'}).$$

(fixme: add proof)

4.9 Denominators

(fixme)

4.10 Examples

Let $E = \mathbf{50a}$ and consider the 4 cusps of denominator 10 on $X_0(50)$. The corresponding first terms of q-expansions at these cusps are

$$\begin{aligned}
a_1(f, \frac{1}{10}) &= \frac{1}{5}\zeta_5^3 - \frac{3}{5}\zeta_5^2 + \frac{3}{5}\zeta_5 - \frac{1}{5}\\
a_1(f, \frac{3}{10}) &= \frac{3}{5}\zeta_5^3 + \frac{6}{5}\zeta_5^2 + \frac{4}{5}\zeta_5 + \frac{2}{5}\\
a_1(f, \frac{7}{10}) &= \frac{2}{5}\zeta_5^3 - \frac{1}{5}\zeta_5^2 - \frac{4}{5}\zeta_5 - \frac{2}{5}\\
a_1(f, \frac{9}{10}) &= -\frac{6}{5}\zeta_5^3 - \frac{2}{5}\zeta_5^2 - \frac{3}{5}\zeta_5 - \frac{4}{5}
\end{aligned}$$

As another examples, let $E = \mathbf{98a}$ and $z = [\frac{1}{14}]$. We computed numerically that

$$\begin{aligned}
f_z(q) = {}& (-0.755001687308946 - 0.172324208281817i)\, q + (0.441471704846525 - 0.916725441095080i)\, q^2\\
&+ (1.39294678431094 + 1.11083799261729i)\, q^3 + (0.696473392155471 - 0.555418996308649i)\, q^4\\
&+ (1.51000337461789 - 0.344648416563641i)\, q^6 + \left(-3.80647894157196 \times 10^{-16} - 3.02371578407382i\right) q^7\\
&+ (0.755001687308946 + 0.172324208281817i)\, q^8 + (-0.441471704846525 + 0.916725441095080i)\, q^9 +\\
&(-0.882943409693050 - 1.83345088219016i)\, q^{12} + (-3.02000674923578 + 0.689296833127282i)\, q^{13}\\
&+ \left(3.80647894157196 \times 10^{-16} + 3.02371578407382i\right) q^{14} + O(q^{15})
\end{aligned}$$

4.11 Applications

One applications of the computation done in this chapter is the norm method to the computation of j-polynomials introduced in Chapter . Recall that the issue with the norm method for non-square free level is computing the expansions of form $f|\gamma$, where γ runs over the set of right coset representatives of $\Gamma_0(N)$ in $SL_2(\mathbb{Z})$. As we have seen, it suffices to compute the expansions of f at all width one cusps.

4.12 Norm of first terms

Let z be a width one cusp of denominator c. Then the first coefficient $a_1(f_z)$ is an element in $K_f(\zeta_{c'})$. For simplicity, we assume that $c' = p^\alpha$ is a prime power. It can be proved using automorphic representations + local langlands correspondence that there exists β such that $p^\beta a_1(f_z) \in \bar{\mathbb{Z}}$. One question is: what prime ideals appears in the prime factorisation of $(a_1(f,z))$? It seems from our numerical data, that

$$\mathrm{ord}_{\mathfrak{q}}(a_1(f_z)) > 0 \implies \mathfrak{q} \cap \mathbb{Z} \equiv \pm 1 \pmod{p}.$$

The following is a table of data.

(fix: add table)

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