Computing congruences of modular forms modulo prime powers

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Plan

(I) Congruences mod ℓ^n.

(II) Computing them.

(III) Modular forms mod ℓ^n.

(IV) Examples and applications.

Congruences mod ℓ^n

Fix $\overline{\mathbb{Q}} \hookrightarrow \overline{\mathbb{Q}}_\ell$. Consider $K/\mathbb{Q}_\ell$ with π_K uniformizer.

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- If $K/\mathbb{Q}_\ell$ is unramified, then

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  congruence mod $(\pi^n) = (\ell^n)$.

Congruences mod ℓ^n

Define congruences mod ℓ^n for $a, b \in \overline{\mathbb{Z}}_\ell$.

For $L/K/\mathbb{Q}_\ell$ finite extensions (inside $\overline{\mathbb{Q}}_\ell$) define

$$\gamma_{L/K}(n) := (n-1)e_{L/K} + 1$$

with $e_{L/K}$ the ramification index.

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- $\lceil \frac{\gamma_{L/K}(n)}{e_{L/K}} \rceil = n$.

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$$\mathbb{Z}/\ell^n\mathbb{Z} \hookrightarrow \mathcal{O}_K/(\pi_K^{\gamma_{K/\mathbb{Q}_\ell}(n)}) \hookrightarrow \mathcal{O}_L/(\pi_L^{\gamma_{L/\mathbb{Q}_\ell}(n)}).$$

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Define

$$a \equiv b \mod \ell^n \Leftrightarrow a - b \in (\pi_K^{\gamma_{K/\mathbb{Q}_\ell}(n)})$$

for any $K/\mathbb{Q}_\ell$ containing a, b.

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Computing congruences mod ℓ^n

Problem: Let $P, Q \in \mathbb{Z}[X]$ be monic coprime polynomials.

For which prime powers ℓ^n are there $\alpha, \beta \in \overline{\mathbb{Z}}$ such that

(i) $P(\alpha) = Q(\beta) = 0$ and

(ii) $\alpha \equiv \beta \mod \ell^n$?

(Partial) Solution:

Reduced resultant

= Congruence ideal/number (our name for it).

Congruence number

$P(X) = \sum_{k=0}^{u} a_k X^{u-k}, \quad Q(X) = \sum_{k=0}^{v} b_k X^{v-k} \in \mathbb{Z}[X]$.

Sylvester map:

$$\begin{array}{ccccc} \mathbb{Z}[X]_{<v} & \times & \mathbb{Z}[X]_{<u} & \xrightarrow{(r,s)\mapsto rP+sQ} & \mathbb{Z}[X]_{<u+v} \\ \{X^{v-1}, \ldots, X, 1\} & & \{X^{u-1}, \ldots, X, 1\} & & \{X^{u+v-1}, \ldots, X, 1\}. \end{array}$$

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Sylvester matrix (for column vectors) with $u = 3$ and $v = 2$:

$$\begin{pmatrix} a_0 & 0 & b_0 & 0 & 0 \\ a_1 & a_0 & b_1 & b_0 & 0 \\ a_2 & a_1 & b_2 & b_1 & b_0 \\ a_3 & a_2 & 0 & b_2 & b_1 \\ 0 & a_3 & 0 & 0 & b_2 \end{pmatrix}$$

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Want to know its image for the basis $\{X^{u+v-1}, \ldots, X, 1\}$.

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I.e. may perform integral column operations.

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Congruence number $c(P, Q)$ is the bottom right entry!

It divides the resultant of P, Q (determinant of $S(P, Q)$).

Congruence number

$$P(X) = X - a, \quad Q(X) = X - b.$$

$$S(P,Q) = \begin{pmatrix} 1 & 1 \\ -a & -b \end{pmatrix}$$

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$\Rightarrow$ Congruence number $c(P,Q) = 3$.

Congruence number

$$P(X) = X^2 + X + 1, \quad Q(X) = (X-1)(X+2) = X^2 + X - 2.$$

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(The resultant is 9.)

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Let $r, s \in \mathbb{Z}[X]$ such that for the congruence number

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Suppose one of the following holds:

- Neither P nor Q has a multiple factor mod ℓ.
- P has no multiple factor mod ℓ and P and r are coprime mod ℓ.
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Computing modular forms

Let f be a newform (level N, weight k) with Fourier expansion:

$$f = f(z) = \sum_{m=1}^{\infty} a_m(f) q^m \text{ with } q = q(z) = e^{2\pi i z}.$$

Fact: All the $a_m(f)$ are integers of some number field.

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$\mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ naturally acts on the Fourier expansion.

$\rightsquigarrow [f]$:= $\mathbb{Z}$-span of $\mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}).f$.

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<u>Fact that makes computations possible:</u>

$a_p(f)$ is a zero of the characteristic polynomial $P_{f,p} \in \mathbb{Z}[X]$ of the Hecke operator T_p acting on $[f]$.

$P_{f,p}$ is easy to compute!

Congruences of modular forms mod ℓ^n

$f = \sum_{m=1}^{\infty} a_m(f) q^m$ a newform (level N_f, weight k).

$g = \sum_{m=1}^{\infty} a_m(g) q^m$ a newform (level N_g, weight k).

Definition. f and g are congruent modulo ℓ^n if

$$a_p(f) \equiv a_p(g) \mod \ell^n \quad \text{for (almost) all primes } p.$$

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If f and g are congruent mod ℓ^n, then
$P_{f,p}$ and $P_{g,p}$ have zeros which are congruent mod ℓ^n.

(Recall: $P_{f,p}$, $P_{f,p}$ characteristic polynomials of T_p on $[f]$ and $[g]$.)

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Some propositions (+ a very believable hypothesis)
$\Rightarrow$ converse is true if compute 'enough' p.

$\leadsto$ Perfect for use of congruence numbers!

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Algorithm:

Congruences of modular forms mod ℓ^n

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$$c_2 := c(P_{f,2}, P_{g,2})$$

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$\dots$.

$\Rightarrow$ Upper bound $u := \gcd(c_2 \cdot 2^\infty, c_3 \cdot 3^\infty, c_5 \cdot 5^\infty, \dots)$.

Prop. f and g are incongruent mod ℓ^m whenever $\ell^m \nmid u$.

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From Theorem (before) often get (under hypothesis):

$$f \equiv g \mod \ell^n \text{ with } \ell^n \mid\mid u.$$

Special case: Level N and Np

Weight 2, level $\Gamma_0(N)$, prime $p \nmid N$. Degeneracy maps:

$$S_2(N) \quad \overset{f(q)\mapsto f(q)}{\underset{f(q)\mapsto f(q^p)}{\rightrightarrows}} \quad S_2(Np).$$

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Span: p-oldspace. Hecke operator $\tilde{T}_p$ on oldspace

$$\begin{pmatrix} T_p & 1_d \\ -p \cdot 1_d & 0_d \end{pmatrix}$$ with T_p Hecke operator on $[f]$.

Let $\tilde{P}_{f,p}$ be the charpoly of $\tilde{T}_p$.

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Modify the algorithm at p:

Compute $c(\tilde{P}_{f,p}, P_{g,p})$ (instead of $c(P_{f,p}, P_{g,p})$).

Examples

Extract from Xavier's table:

N_1	i_1	N_2	i_2	lower bound	upper bound
71	2	71	1	$2 \cdot 3^2$	$2 \cdot 3^2$
109	3	109	1	2^2	2^2
155	4	155	2	2^4	2^4
233	3	233	1	3^3	3^3
613	2	613	1	$7 \cdot 47^2$	$7 \cdot 47^2$
785	2	785	1	7^3	7^3
1073	6	1073	3	$2 \cdot 17^2$	$2 \cdot 17^2$
1481	3	1481	1	$5^2 \cdot 2833$	$5^2 \cdot 2833$
1939	4	1939	3	$37^2 \cdot 4423$	$37^2 \cdot 4423$

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Weak $\neq$ Strong

Weight 2, level $\Gamma_0(71)$. Two classes of newforms both with coefficient field K: $[K:\mathbb{Q}] = 3$ and discriminant $d_K = 257$:

$$[f] : K \begin{array}{c}\longrightarrow\\ \longrightarrow\\ \longrightarrow\end{array} \overline{\mathbb{Q}} \overset{\text{fixed}}{\hookrightarrow} \overline{\mathbb{Q}}_3 \quad \text{and} \quad [g] : K \begin{array}{c}\longrightarrow\\ \longrightarrow\\ \longrightarrow\end{array} \overline{\mathbb{Q}} \overset{\text{fixed}}{\hookrightarrow} \overline{\mathbb{Q}}_3.$$

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Modulo 3, both f_1 and g_1 land in $\mathbb{F}_3$, others in $\mathbb{F}_9$.

$f_1 \equiv g_1 \mod 9$ and $f_1 \not\equiv g_1 \mod 27$

$\Rightarrow$ Only one strong Hecke eigenform modulo 9.

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$\hat{\mathbb{T}} :=$ Hecke algebra completed at 3.

The local factor $\hat{\mathbb{T}}_{\mathfrak{m}}$ belonging to f_1 and g_1 satisfies:

$$\hat{\mathbb{T}}_{\mathfrak{m}} \twoheadrightarrow \hat{\mathbb{T}}_{\mathfrak{m}} \otimes_{\mathbb{Z}_3} \mathbb{Z}/9\mathbb{Z} \cong \mathbb{Z}/9\mathbb{Z}[X]/(X^2) \xrightarrow{X \mapsto 0 \text{ or } X \mapsto 3} \mathbb{Z}/9\mathbb{Z}.$$

Hence: two weak Hecke eigenforms!

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Eisenstein congruences

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Study congruences between newforms and Eisenstein series modulo ℓ^n via the congruence number!

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Thm. (Mazur). In prime level N there is a congruence mod ℓ between a cusp form and the Eisenstein series for all ℓ dividing the numerator of $\frac{N-1}{12}$.

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Eisenstein congruences

Let $f_1, \ldots, f_r$ be all newforms in $S_2(\Gamma_0(N))$ for N prime.

Let ℓ^{n_i} be the highest power of ℓ such that

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Question. Is n at least as big as (or even equal to) the ℓ-valuation of the numerator of $\frac{N-1}{12}$?

Level raising mod ℓ^n

Question. Given: f in level N, weight k, a prime $p \nmid N$ s.t.

$$\ell^n \mid c(P_{f,p}, X-(p+1)) \text{ or } \ell^n \mid c(P_{f,p}, X+(p+1)).$$

Is there g in level Np, weight k such that $f \equiv g \mod \ell^n$?

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but there is no i s.t. $g_i \equiv f \mod 9$!

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Question. Is n at least as big as (or even equal to) the ℓ-valuation of c?

THE END