

M4P58 Modular Forms

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Syllabus

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0 Introduction

Lecture 1
Friday
04/10/19

The following are textbooks.

- Serre, A course in arithmetic, 1973
- J Shurman and F Diamond, A first course in modular forms, 2005

Let

$$f = q \prod_{n=1}^{\infty} (1 - q^n)^2 (1 - q^{11n})^2 = \sum_{n=1} b_n q^n = q - 2q^2 - q^3 + 2q^4 + q^5 + 2q^6 - 2q^7 + \dots,$$

and let a_n be the number of solutions modulo n to the elliptic curve

$$E = \{(x, y) \in \mathbb{Z} \mid y^2 + y = x^3 - x^2 - 10x - 20\}.$$

- Modulo 2, there are $a_2 = 4$ solutions $(0, 0), (0, 1), (1, 0), (1, 1)$.
- Modulo 3, there are $a_3 = 4$ solutions $(1, 0), (1, -1), (-1, 0), (-1, -1)$.
- Modulo 5, there are $a_5 = 4$ solutions $(0, 0), (0, -1), (1, 0), (-1, -1)$.
- Modulo 7, there are $a_7 = 9$ solutions $(1, 3), (2, 2), (2, -3), (-1, 1), (-1, -2), (-2, 1), (-2, -2), (-3, 1), (-3, -2)$.

If $p \neq 11$, then

$$a_p - p = -b_p.$$

The following are some questions.

- What is the relationship between E and f ?
- Can we find similar relationships for other E ?
- How does one prove something like this?

Let

$$\mathbb{H} = \{x + iy \mid x, y \in \mathbb{R}, y > 0\} \subseteq \mathbb{C}.$$

Then \mathbb{H} has an action of

$$\mathrm{SL}_2(\mathbb{R}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbb{R}, ad - bc = 1 \right\}.$$

Modular forms are complex functions on \mathbb{H} with a high degree of symmetry. These functions are symmetric under the action of large discrete subgroups of $\mathrm{SL}_2(\mathbb{R})$, in particular

$$\mathrm{SL}_2(\mathbb{Z}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbb{Z}, ad - bc = 1 \right\} \subseteq \mathrm{SL}_2(\mathbb{R}).$$

Why are these interesting to number theorists? Power series expansions often involve expressions of interest to number theorists. For example,

- Bernoulli numbers,
- divisor functions $\sigma_k(n) = \sum_{d|n} d^k$,
- number of points on elliptic curves, and
- traces of Galois representations.

1 Modular forms of level one

1.1 Modular forms

1.1.1 Modular actions

Let

$$\gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \quad a, b, c, d \in \mathbb{R}.$$

Then $\mathrm{SL}_2(\mathbb{R})$ acts on $\mathbb{C} \cup \{\infty\}$ by

$$\gamma \cdot z = \begin{cases} \frac{az+b}{cz+d} & z \neq -\frac{d}{c} \\ \infty & z = -\frac{d}{c} \end{cases} \quad \gamma \cdot \infty = \frac{a}{c}.$$

One checks that this gives a bijection from $\mathbb{C} \cup \{\infty\}$ to $\mathbb{C} \cup \{\infty\}$, where inverse is given by the inverse matrix

$$\gamma^{-1} = \begin{pmatrix} d & -b \\ -c & a \end{pmatrix},$$

and $\gamma \cdot (\gamma' \cdot z) = \gamma\gamma' \cdot z$. One obtains a left action of $\mathrm{SL}_2(\mathbb{R})$ on $\mathbb{C} \cup \{\infty\}$. An observation is

$$\mathrm{Im} \gamma z = \mathrm{Im} \frac{az+b}{cz+d} = \mathrm{Im} \frac{(az+b)(c\bar{z}+d)}{|cz+d|^2} = \frac{\mathrm{Im}(az+b)(c\bar{z}+d)}{|cz+d|^2} = \frac{(ad-bc)\mathrm{Im} z}{|cz+d|^2}.$$

In particular, if $\gamma \in \mathrm{SL}_2(\mathbb{R})$, then

$$\mathrm{Im} \gamma z = \frac{\mathrm{Im} z}{|cz+d|^2}.$$

So $\mathrm{SL}_2(\mathbb{R})$ preserves $\mathbb{H} \cup \{\infty\}$. More generally, if $\gamma \in \mathrm{GL}_2(\mathbb{R})$, then

$$\mathrm{Im} \gamma z = \frac{\det \gamma \mathrm{Im} z}{|cz+d|^2}.$$

So

$$\mathrm{GL}_2(\mathbb{R})_+ = \{\gamma \in \mathrm{GL}_2(\mathbb{R}) \mid \det \gamma > 0\}$$

preserves $\mathbb{H} \cup \{\infty\}$. Define

$$f|_{k,\gamma} : \mathbb{H} \longrightarrow \mathbb{C} \\ z \longmapsto \det \gamma^{k-1} f(\gamma z) (cz+d)^{-k}, \quad f : \mathbb{H} \rightarrow \mathbb{C}, \quad \gamma \in \mathrm{GL}_2(\mathbb{R})_+, \quad k \in \mathbb{Z},$$

where $\det \gamma^{k-1}$ is the fudge factor, which is one for $\gamma \in \mathrm{SL}_2(\mathbb{R})$, and $(cz+d)^{-k}$ is the twisted action on functions. Check that

$$f|_{k,\mathrm{id}} = f, \quad \left(f|_{k,\gamma}\right)|_{k,\gamma'} = f|_{k,\gamma'\gamma}.$$

This gives, for each k , a left action of $\mathrm{GL}_2(\mathbb{R})_+$ on functions $\mathbb{H} \rightarrow \mathbb{C}$, a **modular action of weight k** . A modular form of weight k will be a sufficiently nice function $f : \mathbb{H} \rightarrow \mathbb{C}$ such that $f|_{k,\gamma} = f$ for all $\gamma \in \mathrm{SL}_2(\mathbb{Z})$. That is, for all $\gamma \in \mathrm{SL}_2(\mathbb{Z})$ and $z \in \mathbb{H}$,

$$f(\gamma z) (cz+d)^{-k} = f(z), \quad \implies \quad f(\gamma z) = f(z) (cz+d)^k,$$

the **modular transformation law of weight k** . The following are some observations.

- Let $k = 0$. Then constant functions satisfy $f(\gamma z) = f(z)$. It will turn out that all functions of weight zero are constant.
- Let k be odd, and $\gamma = -\mathrm{id}$. Then $\gamma z = z$ for all z and $cz+d = -1$, so $f(\gamma z) = f(z) (cz+d)^k$ gives $f(z) = f(z) (-1)^k$, so $f(z) = -f(z)$, so $f(z) = 0$ for all z . So no non-zero functions $f : \mathbb{H} \rightarrow \mathbb{C}$ satisfy the modular transformation law of weight k , for all $\gamma \in \mathrm{SL}_2(\mathbb{Z})$, when k is odd.

Lecture 2
Friday
04/10/19

1.1.2 Review of complex analysis

Let $f : U \rightarrow \mathbb{C}$, for $U \subseteq \mathbb{C}$ open, and let $p \in U$.

Definition 1.1.1. f is **holomorphic** at p if

$$f'(p) = \lim_{\epsilon \rightarrow 0, \epsilon \in \mathbb{C}} \frac{f(p' + \epsilon) - f(p')}{\epsilon}$$

exists for all p' in a neighbourhood of p .

Proposition 1.1.2. f is holomorphic at p implies that f is continuous.

Proposition 1.1.3. f is holomorphic at p implies that f is infinitely differentiable at p , that is $f^{(n)}(p)$ exists for all $n \geq 0$. Moreover, we have

$$f(z) = \sum_{n=0}^{\infty} \frac{f^{(n)}(p)}{n!} (z-p)^n = f(p) + f'(p)(z-p) + \frac{f''(p)}{2} (z-p)^2 + \dots,$$

for all z in a neighbourhood of p .

Corollary 1.1.4. If f is holomorphic and not identically zero on an open set U , then the zeroes of f are isolated on U .

More generally is the following.

Definition 1.1.5. f is **meromorphic** at p if there exists a neighbourhood U of p and $g, h : U \rightarrow \mathbb{C}$ holomorphic on U such that $f = g/h$ on $U \setminus \{p\}$. Such an f has a **Laurent series expansion** at p ,

$$f(z) = \sum_{i=-N}^{\infty} c_i (z-p)^i.$$

The smallest i such that $c_i \neq 0$ is denoted by $\text{ord}_p f$, the **order of vanishing** of f at p .

- If $\text{ord}_p f = -n$ for $n > 0$, we say f has a **pole of order n** .
- If $\text{ord}_p f = n$ for $n > 0$, we say f has a **zero of order n** .

Proposition 1.1.6.

- $\text{ord}_p fg = \text{ord}_p f + \text{ord}_p g$.
- $\text{ord}_p (f + g) \geq \min \{\text{ord}_p f, \text{ord}_p g\}$, with equality if $\text{ord}_p f \neq \text{ord}_p g$.

If f is holomorphic on $U \setminus \{p\}$ for U a neighbourhood of p , then f may or may not be meromorphic at p .

Example. $f(z) = e^{-1/z^2}$ is holomorphic on $\mathbb{C} \setminus \{0\}$, but not meromorphic at zero.

Theorem 1.1.7. Let f be holomorphic on $U \setminus \{p\}$, and there exists $n > 0$ such that

$$\lim_{x \rightarrow p} (x-p)^n f(x)$$

exists. Then f is meromorphic on U , and $\text{ord}_p f \geq -n$.

1.1.3 Modular forms

Definition 1.1.8. $f : \mathbb{H} \rightarrow \mathbb{C}$ is a **weakly modular function of weight k** if

- f is meromorphic on \mathbb{H} , and
- f satisfies the modular transformation law of weight k .

Consider

$$\gamma = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix},$$

so $\gamma z = z + 1$ and $cz + d = 1$. The modular transformation law gives $f(z + 1) = f(z)$. Let

$$D = \{q \mid |q| < 1\}.$$

Can define a function

$$\begin{aligned} g : D \setminus \{0\} &\longrightarrow \mathbb{C} \\ q &\longmapsto f\left(\frac{\log q}{2\pi i}\right), \end{aligned}$$

that is $f(z) = g(e^{2\pi iz})$ for $z \in \mathbb{H}$, where g is holomorphic or meromorphic on $\{z \mid 0 < |z| < 1\}$ if and only if f is holomorphic or meromorphic on \mathbb{H} .

Definition 1.1.9. $f : \mathbb{H} \rightarrow \mathbb{C}$ is a **modular form of weight k** if

1. f satisfies the modular transformation law of weight k ,
2. f is holomorphic on \mathbb{H} , and
3. f is holomorphic at ∞ , so the function $g : D \setminus \{0\} \rightarrow \mathbb{C}$, which is holomorphic on $D \setminus \{0\}$ by 2, extends to a holomorphic function on D .

Then $q \rightarrow 0$ in D if and only if $\text{Im } z \rightarrow +\infty$. Then 3 means $g(q)$ is bounded as $q \rightarrow 0$ so $f(z)$ is bounded as $\text{Im } z \rightarrow +\infty$. For f satisfying 3, $g : D \setminus \{0\} \rightarrow \mathbb{C}$ has a series expansion

$$g(q) = \sum_n a_n q^n = a_0 + a_1 q + \dots$$

in $q = e^{2\pi iz}$. We call this the **q -expansion** for f .

Definition 1.1.10. $f : \mathbb{H} \rightarrow \mathbb{C}$ is a **meromorphic modular form of weight k** if the same conditions 1 to 3 hold, but with holomorphic weakened to meromorphic.

Note. If f is only meromorphic at ∞ then a finite number of negative powers of q can appear.

Example.

- The **modular discriminant**

$$\Delta(z) = q \prod_{n=1}^{\infty} (1 - q^n)^{24} = q - 24q^2 + 252q^3 - 1472q^4 + \dots$$

is a modular form of weight 12.

- The **j -invariant**

$$j(z) = \frac{1}{q} + 744 + 196844q + 21493760q^2 + \dots$$

is a meromorphic modular form of weight 0.

Lecture 3
Monday
07/10/19

1.1.4 Lattice functions

How can we construct modular forms?

Definition 1.1.11. A **lattice** in \mathbb{C} is an abelian subgroup of \mathbb{C} of the form $\mathbb{Z}w_1 + \mathbb{Z}w_2$, where $w_1, w_2 \in \mathbb{C}$ are \mathbb{R} -linearly independent. More generally if V is an \mathbb{R} -vector space, a **lattice** L in V is a discrete abelian subgroup of V that spans V over \mathbb{R} . For $L \subseteq \mathbb{C}$ a lattice and $\lambda \in \mathbb{C}^\times$, let

$$\lambda L = \{\lambda x \mid x \in L\} \subseteq \mathbb{C}.$$

We say that L and λL are **homothetic**. For $z \in \mathbb{H}$, let

$$L_{z,1} = \mathbb{Z} + \mathbb{Z}z = \{az + b \mid a, b \in \mathbb{Z}\} \subseteq \mathbb{C}.$$

A question is when is $L_{z,1}$ homothetic to $L_{z',1}$, and what is a homothety factor?

- Suppose $L_{z,1} = \lambda L_{z',1}$. Then there exist a, b, c, d such that $\lambda z' = az + b$ and $\lambda = cz + d$, so

$$\begin{pmatrix} \lambda z' \\ \lambda \end{pmatrix} = \gamma \begin{pmatrix} z \\ 1 \end{pmatrix}. \quad (1)$$

On the other hand there exist a', b', c', d' such that $z = a'\lambda z' + b'\lambda$ and $1 = c'\lambda z' + d'\lambda$, so

$$\gamma' \begin{pmatrix} \lambda z' \\ \lambda \end{pmatrix} = \begin{pmatrix} z \\ 1 \end{pmatrix}. \quad (2)$$

Then (1) and (2) imply that

$$\gamma' \gamma \begin{pmatrix} z \\ 1 \end{pmatrix} = \begin{pmatrix} z \\ 1 \end{pmatrix},$$

so $\gamma \in \mathrm{SL}_2(\mathbb{Z})$. Moreover (1) implies that $z' = (az + b) / (cz + d)$.

- Conversely, if $\gamma \in \mathrm{SL}_2(\mathbb{Z})$, then $\gamma z = (az + b) / (cz + d)$, so

$$L_{\gamma z,1} = (cz + d)^{-1} L_{az+b,cz+d}.$$

But certainly $L_{az+b,cz+d} \subseteq L_{z,1}$. On the other hand if γ' is inverse to γ ,

$$\begin{pmatrix} z \\ 1 \end{pmatrix} = \gamma' \gamma \begin{pmatrix} z \\ 1 \end{pmatrix} = \gamma \begin{pmatrix} az + b \\ cz + d \end{pmatrix} = \begin{pmatrix} a'(az + b) + b'(cz + d) \\ c'(az + b) + d'(cz + d) \end{pmatrix},$$

so $z \in L_{az+b,cz+d}$ and $1 \in L_{az+b,cz+d}$. So $L_{az+b,cz+d} = L_{z,1}$, so $L_{\gamma z,1} = (cz + d)^{-1} L_{z,1}$.

Definition 1.1.12. A **lattice function of weight k** is a function $F : \{\text{lattices in } \mathbb{C}\} \rightarrow \mathbb{C}$ such that

$$F(\lambda L) = \lambda^{-k} F(L),$$

for all lattices L . Given such an F , can define

$$\begin{array}{ccc} f & : & \mathbb{H} \longrightarrow \mathbb{C} \\ z & \longmapsto & F(L_{z,1}) \end{array}.$$

If F has weight k , then

$$f(\gamma z) = F(L_{\gamma z,1}) = F((cz + d)^{-1} L_{z,1}) = (cz + d)^k F(L_{z,1}) = (cz + d)^k f(z).$$

1.2 Eisenstein series

1.2.1 Eisenstein series

Definition 1.2.1. For $L \in \mathbb{C}$, define the **Eisenstein series**

$$G_k(L) = \sum_{w \in L, w \neq 0} \frac{1}{w^k}, \quad g_k(z) = G_k(L_{z,1}) = \sum_{\substack{m=-\infty \\ (m,n) \neq (0,0)}}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{(mz+n)^k}.$$

Then

$$G_k(\lambda L) = \sum_{w' \in \lambda L, w' \neq 0} \frac{1}{w'^k} = \sum_{w \in L, w \neq 0} \frac{1}{(\lambda w)^k} = \lambda^{-k} G_k(L).$$

Corollary 1.2.2. g_k satisfies the modular transformation law of weight k .

The following are some questions.

- Does G_k , or g_k , converge?
- Is g_k holomorphic or meromorphic on \mathbb{H} ?
- Is g_k holomorphic at ∞ ?
- What is the q -expansion of g_k ?

1.2.2 Convergence and holomorphy on \mathbb{H}

Definition 1.2.3. Let $U \subseteq \mathbb{C}$ be open. A sequence of functions $f_n : U \rightarrow \mathbb{C}$ **converges uniformly on compact sets** to f if for all $C \subseteq U$ compact and $\epsilon > 0$, there exists $N \in \mathbb{Z}$ such that for all $n > N$,

$$|f(z) - f_n(z)| < \epsilon, \quad z \in C.$$

Theorem 1.2.4. A uniform limit of holomorphic functions is holomorphic. If f_n converges to f uniformly on compact sets and f_n is holomorphic on U , then f is holomorphic on U .

Theorem 1.2.5. Let $k \geq 4$. The series $g_k(z)$ converges absolutely and uniformly on compact subsets of \mathbb{H} .

Proof. Let

$$P_{z,r} = \{az + b \mid a, b \in \mathbb{R}, \max(|a|, |b|) = r\} \subseteq \mathbb{C},$$

so $P_{z,r} = rP_{z,1}$, and there are $8r$ points on $P_{z,r} \cap L_{z,1}$. Then

$$g_k(z) = \sum_{r=1}^{\infty} \sum_{w \in L_{z,1} \cap P_{z,r}} \frac{1}{w^k}.$$

The function $z \mapsto |z|$ attains a non-zero minimum $\delta(z)$ on $P_{z,1}$, so on $P_{z,1}$, have $|z| > \delta(z)$, so $1/|z|^k < 1/\delta(z)^k$. On $P_{z,r}$, have $|z| > r\delta(z)$, so $1/|z|^k < 1/r^k \delta(z)^k$. Let $C \subseteq \mathbb{H}$ be compact. Then $z \mapsto \delta(z)$ is a continuous function on C and attains a minimum δ_C . For all $z \in C$ and all $w \in P_{z,r}$, get $|w| > r\delta_C$, so

$$\frac{1}{|w|^k} < \frac{1}{r^k \delta_C^k}.$$

Thus for $z \in C$, $g_k(z)$ is dominated by

$$\sum_{r=1}^{\infty} \frac{8r}{r^k \delta_C^k} = \frac{8}{\delta_C^k} \sum_{r=1}^{\infty} \frac{1}{r^{k-1}},$$

which converges absolutely for $k \geq 4$. □

Corollary 1.2.6. $g_k(z)$ is holomorphic on \mathbb{H} .

Lecture 4
Friday
11/10/19

1.2.3 q -expansion and holomorphy at ∞

The idea is to understand series of the form

$$\sum_{n=-\infty}^{\infty} \frac{1}{(z+n)^k}.$$

Theorem 1.2.7. *A bounded holomorphic function on all of \mathbb{C} is constant.*

Lemma 1.2.8.

1.

$$\frac{\pi^2}{\sin^2 \pi z} = \sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2} = \sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2}.$$

2.

$$\pi \cot \pi z = \frac{1}{z} + \sum_{n=1}^{\infty} \left(\frac{1}{z-n} + \frac{1}{z+n} \right) = \frac{1}{z} + \sum_{n=1}^{\infty} \frac{2z}{z^2 - n^2}.$$

Proof.

1. The right hand side converges absolutely and uniformly on compact subsets of $\mathbb{C} \setminus \mathbb{Z}$, so the right hand side is holomorphic on $\mathbb{C} \setminus \mathbb{Z}$. Locally around $z = n$, the series looks like

$$\sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2} = \cdots + \frac{1}{(z-n+1)^2} + \frac{1}{(z-n)^2} + \frac{1}{(z-n-1)^2} + \cdots = \frac{1}{(z-n)^2} + h_1(z),$$

where $h_1(z)$ is holomorphic in a neighbourhood of $z = n$. Similarly, the left hand side is meromorphic on \mathbb{C} , and the Laurent series near $z = n$ is

$$\frac{\pi^2}{\sin^2 \pi z} = \pi \left(\frac{1}{\pi^2 (z-n)^2} + \frac{1}{3} + \frac{1}{15} \pi^2 (z-n)^2 + \cdots \right) = \frac{1}{(z-n)^2} + h_2(z),$$

where $h_2(z)$ is a holomorphic function. So the difference

$$g(z) = \sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2} - \frac{\pi^2}{\sin^2 \pi z}$$

is meromorphic on \mathbb{C} and holomorphic on $\mathbb{C} \setminus \mathbb{Z}$, and the Laurent expression around $z = n$ is

$$g(z) = \frac{1}{(z-n)^2} + h_1(z) - \left(\frac{1}{(z-n)^2} + h_2(z) \right) = h_1(z) - h_2(z),$$

so $g(z)$ is holomorphic at $z = n$ for all n . Consider $t \rightarrow \pm\infty$ for $z = a + it$. The right hand side is

$$R = \sum_{n=-\infty}^{\infty} \frac{1}{(z-n)^2} = \sum_{n=a-N}^{a+N} \frac{1}{(z-n)^2} + \sum_{n=-\infty}^{a-N-1} \frac{1}{(z-n)^2} + \sum_{n=a+N+1}^{\infty} \frac{1}{(z-n)^2} = R_0 + R_- + R_+,$$

where R_0 has finitely many terms that converge to less than $\epsilon/2$ as $t \rightarrow \pm\infty$ and $R_- + R_+ < \epsilon/2$ for $N \gg 0$ independent of t , so $R < \epsilon$ converges to zero. Similarly, the left hand side is

$$\left| \frac{\pi^2}{\sin^2 \pi z} \right| = \left| \frac{2\pi^2}{e^{\pi i z} - e^{-\pi i z}} \right| \rightarrow 0,$$

so $\lim_{t \rightarrow \infty} g(a + it) = 0$. Moreover, $g(z+1) = g(z)$ for all z . Then

$$S = \{z \in \mathbb{C} \mid n-1 \leq \operatorname{Re} z \leq n, -N \leq \operatorname{Im} z \leq N\}, \quad n \in \mathbb{Z}$$

is compact, so $|g(z)|$ attains a maximum in S , so $g(z)$ is bounded in S . Since $g(z)$ is also bounded in $R_- + R_+$, $g(z)$ is bounded in \mathbb{C} , so g is constant. Since $\lim_{t \rightarrow \infty} g(a + it) = 0$, $g = 0$.

2. Check that the right hand side converges absolutely and uniformly on compact subsets of $\mathbb{C} \setminus \mathbb{Z}$, so the right hand side is meromorphic on $\mathbb{C} \setminus \mathbb{Z}$. Similarly, the left hand side is also meromorphic on $\mathbb{C} \setminus \mathbb{Z}$. Comparing derivatives,

$$-\frac{\pi^2}{\sin^2 \pi z} = -\frac{1}{z^2} - \sum_{n=1}^{\infty} \left(\frac{1}{(z-n)^2} + \frac{1}{(z+n)^2} \right),$$

so the difference is constant. Let $z = \frac{1}{2}$. The left hand side is $\pi \cot \pi/2 = 0$ and the right hand side is

$$\frac{2}{1} + \left(-\frac{2}{1} + \frac{2}{3} \right) + \left(-\frac{2}{3} + \frac{2}{5} \right) + \cdots \rightarrow 0, \quad n \rightarrow \infty,$$

so the difference is zero. □

Thus

$$\frac{1}{z} + \sum_{n=1}^{\infty} \left(\frac{1}{z-n} + \frac{1}{z+n} \right) = \pi \cot \pi z = \pi i \frac{e^{\pi i z} + e^{-\pi i z}}{e^{\pi i z} - e^{-\pi i z}} = \pi i \frac{q+1}{q-1} = \pi i - \frac{2\pi i}{1-q} = \pi i - 2\pi i \sum_{n=0}^{\infty} q^n.$$

Take $\frac{d^{k-1}}{dz^{k-1}}$. For $k \geq 2$ even, get

$$-(k-1)! \sum_{n=-\infty}^{\infty} \frac{1}{(z+n)^k} = -(2\pi i)^k \sum_{n=1}^{\infty} n^{k-1} q^n,$$

so

$$\sum_{n=-\infty}^{\infty} \frac{1}{(z+n)^k} = \frac{(2\pi i)^k}{(k-1)!} \sum_{n=1}^{\infty} n^{k-1} q^n.$$

Collecting powers of q ,

$$\begin{aligned} g_k(z) &= \sum_{\substack{m=-\infty \\ (m,n) \neq (0,0)}}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{(mz+n)^k} \\ &= 2 \sum_{n=1}^{\infty} \frac{1}{n^k} + 2 \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{(mz+n)^k} \\ &= 2\zeta(k) + \frac{2(2\pi i)^k}{(k-1)!} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} n^{k-1} q^{nm} \\ &= 2\zeta(k) + \frac{2(2\pi i)^k}{(k-1)!} \sum_{n=1}^{\infty} \sigma_{k-1}(n) q^n \end{aligned} \quad \begin{aligned} \zeta(s) &= \sum_{n=1}^{\infty} n^{-s} \\ \sigma_{k-1}(n) &= \sum_{d|n, d>0} d^{k-1}. \end{aligned}$$

Corollary 1.2.9. $g_k(z)$ is holomorphic at ∞ . In particular, g_k is a modular form of weight k .

1.2.4 Bernoulli numbers

Definition 1.2.10. The **Bernoulli numbers** b_k are defined by

$$\sum_{k=0}^{\infty} b_k \frac{x^k}{k!} = \frac{x}{e^x - 1},$$

a formal power series with rational coefficients.

Then

$$b_0 = 1, \quad b_1 = -\frac{1}{2}, \quad b_2 = \frac{1}{6}, \quad b_3 = 0, \quad b_4 = -\frac{1}{20}, \quad \dots, \quad b_{2k} \in \mathbb{Q}, \quad b_{2k+1} = 0, \quad \dots$$

Proposition 1.2.11. *For all even k ,*

$$\zeta(k) = -b_k \frac{(2\pi i)^k}{2k!}.$$

Proof. On one hand,

$$\pi z \cot \pi z = \pi i z + \frac{2\pi i z}{e^{2\pi i z} - 1} = \pi i z + \sum_{k=0}^{\infty} b_k \frac{(2\pi i z)^k}{k!}.$$

On the other hand,

$$\begin{aligned} \pi \cot \pi z &= \frac{1}{z} + \sum_{n=1}^{\infty} \frac{2z}{z^2 - n^2} = \frac{1}{z} - \frac{2z}{n^2} \sum_{n=1}^{\infty} \frac{1}{1 - z^2/n^2} \\ &= \frac{1}{z} - \sum_{n=1}^{\infty} \frac{2}{z} \sum_{k=1}^{\infty} \left(\frac{z^2}{n^2}\right)^k = \frac{1}{z} - \frac{2}{z} \sum_{k=1}^{\infty} z^{2k} \sum_{n=1}^{\infty} \frac{1}{n^{2k}} = \frac{1}{z} - \frac{2}{z} \sum_{k=1}^{\infty} \zeta(2k) z^{2k}, \end{aligned}$$

so

$$\pi i z + \sum_{k=0}^{\infty} b_k \frac{(2\pi i z)^k}{k!} = \pi z \cot \pi z = 1 - 2 \sum_{k=1}^{\infty} \zeta(2k) z^{2k}.$$

Comparing,

$$b_{2k} \frac{(2\pi i)^{2k}}{(2k)!} = -2\zeta(2k),$$

get the desired formula. □

So

$$g_k(z) = \frac{-b_k (2\pi i)^k}{k!} + \frac{2(2\pi i)^k}{(k-1)!} \sum_{n=1}^{\infty} \sigma_{k-1}(n) q^n.$$

Set the **normalised Eisenstein series**

$$E_k = \frac{g_k}{2\zeta(k)} = 1 - \frac{2k}{b_k} \sum_{n=1}^{\infty} \sigma_{k-1}(n) q^n.$$

Example.

$$\begin{aligned} E_4 &= 1 + 240 \sum_{n=1}^{\infty} \sigma_3(n) q^n, & E_6 &= 1 - 504 \sum_{n=1}^{\infty} \sigma_5(n) q^n, \\ E_8 &= 1 + 480 \sum_{n=1}^{\infty} \sigma_7(n) q^n, & E_{12} &= 1 + \frac{65520}{691} \sum_{n=1}^{\infty} \sigma_{11}(n) q^n. \end{aligned}$$

An observation is if f is modular of weight k and g is modular of weight k' , then fg is modular of weight $k + k'$, and if $k = k'$, then $f + g$ is modular of weight k .

Example. Important examples.

- The **modular discriminant**

$$\Delta(z) = \frac{E_4 - E_6^2}{1728} = q - 24q^2 + 252q^3 + \dots$$

is a modular form of weight 12.

- The **j-invariant**

$$j(z) = \frac{E_4^3}{\Delta} = \frac{1}{q} + 744 + 196844q + \dots$$

is a meromorphic modular form of weight 0.

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1.3 Controlling modular forms

1.3.1 The fundamental domain

The idea is to control the action of $\mathrm{SL}_2(\mathbb{Z})$ on \mathbb{H} . If $f : \mathbb{H} \rightarrow \mathbb{C}$ satisfies $f(\gamma z) = (cz + d)^k f(z)$ for all $\gamma \in \mathrm{SL}_2(\mathbb{Z})$, and if $D \subseteq \mathbb{H}$ such that D meets every $\mathrm{SL}_2(\mathbb{Z})$ -orbit in \mathbb{H} , then f is determined by its values on D .

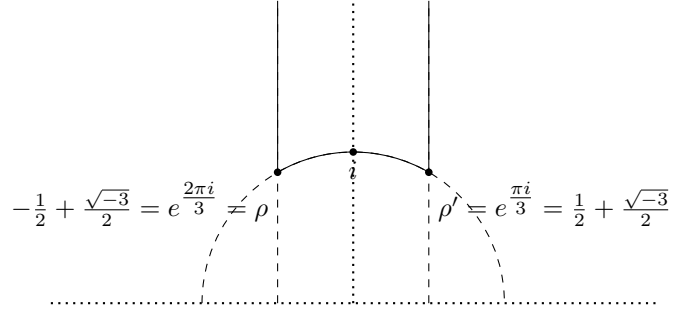
Definition 1.3.1. Let G be a group acting continuously on a complex analytic space X , such as $X = \mathbb{H}$. A subset $D \subseteq X$ is a **fundamental domain** for the action of G if

- D meets every G -orbit in X ,
- the subset $\{x \in D \mid \exists g \in G, gx \in D, gx \neq x\}$ has measure zero, and
- D is closed in X .

Define

$$\mathcal{D} = \{z \in \mathbb{H} \mid \tfrac{1}{2} \leq \operatorname{Re} z \leq \tfrac{1}{2}, |z| \geq 1\} \subseteq \mathbb{H},$$

so



Let

$$S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} : z \mapsto -\frac{1}{z}, \quad T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} : z \mapsto z + 1,$$

and let $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Z})$ be the subgroup generated by S and T . We will see later that $\Gamma = \mathrm{SL}_2(\mathbb{Z})$.

Theorem 1.3.2.

1. For all $z \in \mathbb{H}$, there exists $\gamma \in \Gamma$ such that $\gamma z \in \mathcal{D}$.
2. Suppose $z, z' \in \mathcal{D}$ and $\gamma \in \mathrm{SL}_2(\mathbb{Z})$ with $\gamma z = z'$. Then either
 - $z = z'$,
 - $\operatorname{Re} z = \pm \frac{1}{2}$ and $z' = z \mp 1$, or
 - $|z| = 1$ and $z' = -1/z$.

In particular, if $z \neq z'$, then z and z' are on the boundary of \mathcal{D} .

3. For $z \in \mathcal{D}$, let I_z be the stabiliser of z in $\mathrm{SL}_2(\mathbb{Z})$, that is

$$I_z = \{\gamma \in \mathrm{SL}_2(\mathbb{Z}) \mid \gamma z = z\}.$$

Then $I_z = \{\pm I\}$ unless

- $z = i$, where $I_z = \{\pm I, \pm S\}$,
- $z = \rho$, where $I_z = \{\pm I, \pm (ST), \pm (T^{-1}S)\}$, or
- $z = \rho'$, where $I_z = \{\pm I, \pm (TS), \pm (ST^{-1})\}$.

Corollary 1.3.3. $\Gamma = \mathrm{SL}_2(\mathbb{Z})$.

Proof. Fix $\gamma \in \mathrm{SL}_2(\mathbb{Z})$ and $z \in \mathring{\mathcal{D}}$ so $\mathrm{SL}_2(\mathbb{Z})z \cap \mathcal{D} = \{z\}$ and $I_z = \{\pm I\}$. Consider γz . There exists $\gamma' \in \Gamma$ such that $\gamma'\gamma z \in \mathcal{D}$, so $\gamma'\gamma z = z$. So $\gamma'\gamma = \pm I$, so $\gamma = \pm \gamma'^{-1}$. But $\gamma'^{-1} \in \Gamma$ and $-I = S^2 \in \Gamma$, so $\gamma \in \Gamma$. \square

Proof of Theorem 1.3.2. Recall $\operatorname{Im} \gamma z = \operatorname{Im} z / |cz + d|^2$ for $\gamma \in \operatorname{SL}_2(\mathbb{Z})$.

1. As c and d vary, $\{cz + d\}$ forms a lattice in \mathbb{C} , so there exist only finitely many c and d such that $|cz + d| < 1$. So $\operatorname{Im} \gamma z$ attains a maximum as γ varies over Γ , so there exists $\gamma \in \Gamma$ such that $\operatorname{Im} \gamma z$ is maximal. There exists $n \in \mathbb{Z}$ such that $T^n \gamma z$ has real part between $-\frac{1}{2}$ and $\frac{1}{2}$. Consider $|T^n \gamma z|$. If this is less than one, then

$$\operatorname{Im} ST^n \gamma z = \operatorname{Im} \frac{-1}{T^n \gamma z} > \operatorname{Im} T^n \gamma z = \operatorname{Im} \gamma z.$$

Since $ST^n \gamma \in \Gamma$, this contradicts maximality so $|T^n \gamma z| \geq 1$, so $T^n \gamma z \in \mathcal{D}$.

- 2, 3. Let $z, z' \in \mathcal{D}$ such that $\gamma z = z'$. Without loss of generality $\operatorname{Im} z' \geq \operatorname{Im} z$, so $|cz + d| \leq 1$. Note that $|cz + d| \geq \operatorname{Im}(cz + d) \geq \frac{\sqrt{3}}{2}c$, so $c = -1, 0, 1$. Note that can replace γ with $-\gamma$ if convenient.

$c = 0$. Then $ad = 1$, so can assume $a = d = 1$, so $\gamma z = z + b$. Since $z, z + b \in \mathcal{D}$, $b = \pm 1$ and $\operatorname{Re} z = \mp \frac{1}{2}$.

$c = 1$. Have $|z + d| \leq 1$ and $|z| \geq 1$, so $d = -1, 0, 1$.

$d = 0$. Then $|z| = 1$, and $\gamma z = (az - 1)/z = a - 1/z$. The only possibilities are

- * $a = 0$ and $\gamma = S$,
- * $a = 1$ and $\gamma = TS$, so $z = \rho'$, or
- * $a = -1$ and $\gamma = T^{-1}S$, so $z = \rho$.

$d = 1$. Then $z = \rho$, and $\gamma z = ((b + 1)z + b)/(z + 1) = b + 1 - 1/(z + 1)$, so $b = 0$ or $b = -1$.

$d = -1$. Then $z = \rho'$ is similar.

$c = -1$. Similar.

□

1.3.2 Further review of complex analysis

Recall that on any compact set, a meromorphic function has only finitely many zeroes and poles. If $f(z) = g(e^{2\pi iz})$ is meromorphic at ∞ and g is meromorphic on $D = \{q \mid |q| < 1\}$, zeroes and poles of g are discrete with respect to q , and $\operatorname{Im} z \gg 0$ if and only if $|q| < \epsilon$.

Definition 1.3.4. Let $U \subseteq \mathbb{C}$ be open, and let $f : U \rightarrow \mathbb{C}$ be meromorphic on U . If f has a pole at p , can write

$$f(z) = \sum_{n=\operatorname{ord}_p f < 0}^{\infty} a_n (z - p)^n.$$

The coefficient a_{-1} is called the **residue** $\operatorname{Res}_p f$ of f at p .

Theorem 1.3.5 (Residue theorem). Let V be a region in \mathbb{C} whose boundary ∂V is a simple closed curve. Then

$$\frac{1}{2\pi} \int_{\partial V} f(z) dz = \sum_{p \in V \text{ pole of } f} \operatorname{Res}_p f.$$

Definition 1.3.6. Let f be meromorphic on $U \subseteq \mathbb{C}$ open. Then the **logarithmic derivative** $d \log f$ is the function f'/f .

If $f(z) = c_n (z - p)^n + c_{n+1} (z - p)^{n+1} + \dots$, then if $n \neq 0$, then the leading term of f' is $nc_n (z - p)^{n-1}$ and the leading term of f is $c_n (z - p)^n$, so the leading term of f'/f is $n(z - p)^{-1}$. If $n = 0$, then f'/f is holomorphic. So f'/f is meromorphic with simple poles precisely at the points where $\operatorname{ord}_p f \neq 0$, and $\operatorname{Res}_p f'/f$ at such p is $\operatorname{ord}_p f$.

Theorem 1.3.7 (Argument principle).

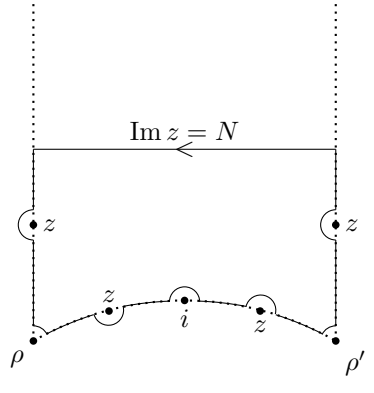
$$\frac{1}{2\pi i} \int_{\partial V} \frac{f'(z)}{f(z)} dz = \sum_{p \in V} \operatorname{ord}_p f.$$

1.3.3 Controlling modular forms

Theorem 1.3.8 ($k/12$ -formula). *Let f be a non-zero meromorphic modular form of weight k . Then*

$$\text{ord}_\infty f + \frac{\text{ord}_\rho f}{3} + \frac{\text{ord}_i f}{2} + \sum_{p \in \text{SL}_2(\mathbb{Z}) \backslash \mathbb{H}, p \sim \{i, \rho\}} \text{ord}_p f = \frac{k}{12}.$$

Proof. Consider the closed curve $C_{N, \epsilon}$,



where the z 's are zeroes or poles of f , and the circles are of radius ϵ . Consider

$$\frac{1}{2\pi i} \int_{C_{N, \epsilon}} \frac{f'(z)}{f(z)} dz = \sum_{p \in \text{SL}_2(\mathbb{Z}) \backslash \mathbb{H}, p \sim \{i, \rho\}} \text{ord}_p f, \quad \epsilon \rightarrow 0.$$

So it suffices to show

$$\lim_{\epsilon \rightarrow 0, N \rightarrow \infty} \frac{1}{2\pi i} \int_{C_{N, \epsilon}} \frac{f'(z)}{f(z)} dz = -\text{ord}_\infty f - \frac{\text{ord}_\rho f}{3} - \frac{\text{ord}_i f}{2} + \frac{k}{12}.$$

The vertical parts of the boundary cancel. The integral over the circular part of $\partial \mathcal{D}$ approaches

$$\frac{1}{2\pi i} \int_\rho^i \frac{f'(z)}{f(z)} dz + \frac{1}{2\pi i} \int_i^{\rho'} \frac{f'(z)}{f(z)} dz = \frac{1}{2\pi i} \left(\int_\rho^i \frac{f'(z)}{f(z)} dz - \int_\rho^i \frac{f'(-1/z)}{f(-1/z)} dz \right)$$

Since $f(-1/z) = z^k f(z)$,

$$d(z^k f(z)) = (kz^{k-1} f(z) + z^k f'(z)) dz,$$

so

$$\frac{1}{2\pi i} \int_\rho^i \frac{f'(z)}{f(z)} dz + \frac{1}{2\pi i} \int_i^{\rho'} \frac{f'(z)}{f(z)} dz = \frac{1}{2\pi i} \int_\rho^i \frac{f'(z)}{f(z)} dz - \frac{kz^{k-1} f(z) + z^k f'(z)}{z^k f(z)} dz = -\frac{1}{2\pi i} \int_\rho^i \frac{k}{z} dz = \frac{k}{12}.$$

Since $dq = 2\pi i q dz$, the top part is

$$\frac{1}{2\pi i} \int_{\frac{1}{2} - iN}^{\frac{1}{2} - iN} \frac{f'(z)}{f(z)} dz = -\frac{1}{2\pi i} \int_{\text{circle of radius } \epsilon} \frac{g'(q)}{g(q)} dq = -\text{ord}_\infty f.$$

Near i , $f'/f = \text{ord}_i f (z - i)^{-1} + h(z)$, where $h(z)$ is holomorphic and $h(z) \rightarrow 0$ as $\epsilon \rightarrow 0$. Then the circle $C_{\epsilon, i}$ of radius ϵ centered at i is

$$\lim_{\epsilon \rightarrow 0} \frac{1}{2\pi i} \int_{C_{\epsilon, i}} \frac{f'(z)}{f(z)} dz = \lim_{\epsilon \rightarrow 0} \frac{1}{2\pi i} \int_{\text{arc of half circle centered at } i} \frac{\text{ord}_i f}{z - i} dz = -\frac{\text{ord}_i f}{2}.$$

Similarly, at ρ and ρ' , get that the circles $C_{\epsilon, \rho}$ and $C_{\epsilon, \rho'}$ of radius ϵ centered at ρ and ρ' are

$$\lim_{\epsilon \rightarrow 0} \frac{1}{2\pi i} \int_{C_{\epsilon, \rho}} \frac{f'(z)}{f(z)} dz = \lim_{\epsilon \rightarrow 0} \frac{1}{2\pi i} \int_{C_{\epsilon, \rho'}} \frac{f'(z)}{f(z)} dz = -\frac{\text{ord}_\rho f}{6},$$

which gives $-\text{ord}_\rho f/3$. □

1.3.4 Holomorphic modular forms

Let

$$M_k = \{\text{holomorphic modular forms of weight } k\},$$

and let

$$S_k = \{\text{cusp forms of weight } k\} = \{f \in M_k \mid \text{ord}_\infty f > 0\} \subseteq M_k.$$

Corollary 1.3.9.

- $M_k = 0$ if $k < 0$, $k = 2$, or k odd.
- M_0 are constants.
- $M_4 = \mathbb{C}E_4$, where $\text{ord}_p E_4 = 1$ and no other zeroes.
- $M_6 = \mathbb{C}E_6$, where $\text{ord}_i E_6 = 1$ and no other zeroes.
- $M_8 = \mathbb{C}E_8$, where $\text{ord}_p E_8 = 2$ and no other zeroes.
- $M_{10} = \mathbb{C}E_{10}$, where $\text{ord}_p E_{10} = \text{ord}_i E_{10} = 1$ and no other zeroes.
- $M_{12} = \mathbb{C}E_{12} \oplus \mathbb{C}\Delta$, where $\text{ord}_\infty \Delta = 1$ and no other zeroes.

Corollary 1.3.10. $\Delta : M_k \rightarrow S_{k+12}$ is an isomorphism. On the other hand,

$$M_k \cong \mathbb{C}E_k \oplus S_k, \quad k \geq 4 \text{ even},$$

so

$$M_k \cong \mathbb{C}E_k \oplus \cdots \oplus \mathbb{C}E_{k-12r}\Delta^r, \quad k - 12r \in \{0, 4, 6, 8, 10, 14\}.$$

So for $k \geq 4$, the set

$$\begin{cases} E_k, \dots, E_{k-12\lfloor k/12 \rfloor} \Delta^{\lfloor k/12 \rfloor} & k \not\equiv 2 \pmod{12} \\ E_k, \dots, E_{14} \Delta^{\lfloor k/12 \rfloor - 1} & k \equiv 2 \pmod{12} \end{cases}$$

is a basis for M_k .

Corollary 1.3.11. $E_4^2 = E_8$ and $E_4 E_6 = E_{10}$.

A variant is to write $k = 4n + 6m$ with $m = 0, 1$ and $n \geq 0$, for $k \geq 4$. Then $M_k = \mathbb{C}E_4^n E_6^m \oplus S_k$ gives a basis

$$E_4^n E_6^m, \dots, E_4^{n-3\lfloor n/3 \rfloor} E_6^m \Delta^{\lfloor n/3 \rfloor}$$

for M_k . Since $\Delta = (E_4^3 - E_6^2)/1728$, we see every modular form of weight k is a polynomial in E_4 and E_6 , and

$$\Delta \in q + q^2 \mathbb{Z}[[q]], \quad E_4^n E_6^m \in 1 + q\mathbb{Z}[[q]], \quad E_4^{n-3\lfloor n/3 \rfloor} E_6^m \Delta \in q + q^2 \mathbb{Z}[[q]], \quad \dots$$

have integer coefficients. The upshot is if the q -expansion of f has integer coefficients, then f is an integer combination of

$$E_4^n E_6^m, \dots, E_4^{n-3\lfloor n/3 \rfloor} E_6^m \Delta^{\lfloor n/3 \rfloor}.$$

Notation. $M_k(\mathbb{Z}) \subseteq M_k$ consists of modular forms with integer q -expansions.

Theorem 1.3.12. $M_k(\mathbb{Z})$ spans M_k , and $f \in M_k$ lies in $M_k(\mathbb{Z})$ if and only if f is an integral polynomial in E_4, E_6, Δ .

Definition 1.3.13. A **graded ring** is a ring R , together with a direct sum decomposition, as abelian groups,

$$R = \bigoplus_{i \in \mathbb{Z}} R_i,$$

such that $R_i \cdot R_j \subseteq R_{i+j}$ for all $i, j \in \mathbb{Z}$.

Example.

- $R = \mathbb{C}[X, Y]$, where R_i are polynomials homogeneous of degree i .
- $R = \bigoplus_{k \in \mathbb{Z}} M_k$.

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Let $\mathbb{C}[X, Y]$ be graded with $\deg X = 4$ and $\deg Y = 6$. Have a homomorphism of graded rings

$$\begin{aligned} \mathbb{C}[X, Y] &\longrightarrow \bigoplus_{k \in \mathbb{Z}} M_k \\ (X, Y) &\longmapsto (E_4, E_6) \end{aligned}.$$

Theorem 1.3.14. *This is an isomorphism of graded rings.*

Proof. This map is surjective, since every $f \in M_k$ is a polynomial in E_4 and E_6 . Remains to show this map is injective. Suppose not. There exists $P(X, Y)$, homogeneous of degree k , such that $P(E_4, E_6) = 0$. Write $k = 4n + 6m$ with $m = 0, 1$. If $P = c_0 X^n Y^m + \cdots + c_r X^{n-3r} Y^{m+2r}$ where $r = \lfloor n/3 \rfloor$, then

$$c_0 E_4^n E_6^m + \cdots + c_r E_4^{n-3r} E_6^{m+2r} = 0.$$

Dividing by $E_4^{n-3r} E_6^{m+2r}$, get $Q(E_4^3/E_6^2) = 0$ where $Q(X) = c_0 X^r + \cdots + c_r$. Since the roots of Q are discrete, and E_4^3/E_6^2 is non-constant, this is impossible. \square

1.3.5 Meromorphic modular forms

Note. The meromorphic modular forms of weight zero form a field. For example, $j(z) = E_4^3/\Delta = 1728E_4^3/(E_4^3 - E_6^2)$ is a non-constant meromorphic modular form, with a pole of order one at ∞ , a zero of order three at ρ , and no other zeroes or poles.

Theorem 1.3.15. *j gives a bijection between $\mathrm{SL}_2(\mathbb{Z}) \backslash \mathbb{H}$ and \mathbb{C} .*

Proof. Given $\lambda \in \mathbb{C}$, want $z \in \mathbb{H}$ such that $j(z) = \lambda$. Consider $g = j - \lambda$. This is meromorphic of weight zero. There is a pole at ∞ , and no other poles, and

$$\mathrm{ord}_\infty g + \frac{\mathrm{ord}_\rho g}{3} + \frac{\mathrm{ord}_i g}{2} + \sum_{p \in \mathrm{SL}_2(\mathbb{Z}) \backslash \mathbb{H}, p \neq \{i, \rho\}} \mathrm{ord}_p g = 0.$$

The only possibilities are

- g has a zero at ρ of order three, and no other zeroes,
- g has a zero at i of order two, and no other zeroes, or
- g has a simple zero somewhere else, and no others.

In each case, the zero of g is a unique $\mathrm{SL}_2(\mathbb{Z})$ -orbit on which $j(z) = \lambda$. So j is bijective. \square

Theorem 1.3.16. *Every meromorphic modular form of weight zero is a rational function in j . That is, the field of meromorphic modular forms is $\mathbb{C}(j)$.*

Proof. Let g be meromorphic of weight zero. Then g has finitely many $\mathrm{SL}_2(\mathbb{Z})$ -orbits worth of poles in \mathbb{H} . Saw last time that j is holomorphic in \mathbb{H} . If p is a pole of g , then $(j(z) - j(p))^{n_p}$ is holomorphic on \mathbb{H} and zero at $z = p$. Doing this for all poles, there exists $P \in \mathbb{C}[X]$ such that $P(j)g(z)$ is holomorphic on \mathbb{H} . Then for some m , $P(j)g(z)\Delta^m$ is holomorphic of weight $12m$. So it suffices to show if h is holomorphic of weight $12m$, then h/Δ^m is a rational function in j , since if $P(j)g(z)\Delta^m = h$ then $P(j)g(z) \in \mathbb{C}(j)$, so $g(z) \in \mathbb{C}(j)$. Then h is a sum of terms

$$h = \sum_{a,b} c_{a,b} E_4^a E_6^b, \quad c_{a,b} \in \mathbb{C}, \quad 4a + 6b = 12m.$$

Considering this equation modulo four and modulo three, find $3 \mid a$ and $2 \mid b$, so

$$\frac{h}{\Delta^m} = \sum_{a,b} c_{a,b} \left(\frac{E_4^3}{\Delta} \right)^{\frac{a}{3}} \left(\frac{E_6^2}{\Delta} \right)^{\frac{b}{2}}.$$

So it suffices to show E_4^3/Δ and E_6^2/Δ are rational functions in j . Then $j = E_4^3/\Delta$, and

$$\frac{E_6^2}{\Delta} = \frac{1728E_6^2}{E_4^3 - E_6^2} = \frac{1728(E_6^2 - E_4^3) + 1728E_4^3}{E_4^3 - E_6^2} = -1728 + \frac{1728E_4^3}{E_4^3 - E_6^2} = j - 1728.$$

\square

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1.4 Theta series

Let $L \subseteq \mathbb{R}^n$ be a lattice. For $x, y \in L$, $x \cdot y \in \mathbb{R}$. Suppose $x \cdot y \in \mathbb{Z}$ for all $x, y \in L$. A question is for $n \in \mathbb{Z}$, how many $x \in L$ have $x \cdot x = n$? The rough idea is to form the series

$$\sum_{x \in L} q^{x \cdot x} = \sum_{n=0}^{\infty} a_n q^n, \quad a_n = \# \{x \in L \mid x \cdot x = n\}.$$

We will show, with some slight modifications, and extra hypotheses on L , this generating function turns out to be a modular form.

1.4.1 Quadratic forms

Fix a lattice $L \subseteq \mathbb{R}^n$, so

$$L = \mathbb{Z} \cdot e_1 \oplus \cdots \oplus \mathbb{Z} \cdot e_n.$$

Given these e_i , form a matrix A such that $A_{ij} = e_i \cdot e_j$.

Note. $A = B^T B$, where B is the matrix whose columns are the e_i , and $|\det B|$ is the volume of the parallelogram spanned by e_i , so $\det A = (\det B)^2 > 0$.

Definition 1.4.1. The **dual lattice** L^\vee is the set of $y \in \mathbb{R}^n$ such that $y \cdot x \in \mathbb{Z}$ for all $x \in L$.

Let f_1, \dots, f_n be the dual basis to e_1, \dots, e_n , that is the unique set of solutions f_1, \dots, f_n such that

$$f_i \cdot e_j = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}.$$

Then L^\vee is spanned by the f_i . Clearly $f_i \in L^\vee$ for all i . Conversely, if $y \in L^\vee$, then $y \cdot e_i = a_i \in \mathbb{Z}$, then $y = \sum_{i=1}^n a_i f_i$.

Proposition 1.4.2. Let $C = A^{-1}$. Then

$$f_i = \sum_{j=1}^n C_{ij} e_j.$$

Proof.

$$f_i \cdot e_k = \sum_{j=1}^n C_{ij} e_j \cdot e_k = \sum_{j=1}^n C_{ij} A_{jk} = (CA)_{ik} = \begin{cases} 1 & i = k \\ 0 & i \neq k \end{cases}.$$

□

Definition 1.4.3. A lattice L is **self-dual** if $L^\vee = L$ as subsets of \mathbb{R}^n .

Proposition 1.4.4. L is self-dual if and only if the associated matrix A has integer entries and determinant 1.

Proof. Clearly if $L = L^\vee$, then $e_i \cdot e_j \in \mathbb{Z}$, so A has integer entries. Since $L^\vee \subseteq L$, f_i is an integer combination of the e_j , so $C = A^{-1}$ has integer entries. So $\det A = \pm 1$, but already saw $\det A > 0$. Conversely if A has integer entries and determinant one, $C = A^{-1}$ has integer entries. Then A has integer entries implies that $e_i \cdot e_j \in \mathbb{Z}$ for all i and j , so $e_i \in L^\vee$ for all i , so $L \subseteq L^\vee$. Similarly, C has integer entries implies that $L^\vee \subseteq L$. □

If L is self-dual, get an integer-valued **quadratic form**

$$\begin{aligned} Q_L : \quad \mathbb{Z}^n &\longrightarrow \mathbb{Z} \\ (a_1, \dots, a_n) &\longmapsto (a_1 e_1 + \cdots + a_n e_n) \cdot (a_1 e_1 + \cdots + a_n e_n) = (a_1 \ \dots \ a_n) A \begin{pmatrix} a_1 \\ \vdots \\ a_n \end{pmatrix}. \end{aligned}$$

A question is given m , how often does Q_L represent m ?

1.4.2 Fourier analysis

Let f be a C^∞ function on $\mathbb{R}^n \rightarrow \mathbb{C}$.

Definition 1.4.5. We will say f is **rapidly decreasing** if for all m ,

$$\|x\|^m \cdot |f(x)| \rightarrow 0, \quad |x| \rightarrow \infty,$$

where $|x| = (x \cdot x)^{1/2}$. For $f \in C^\infty$, rapidly decreasing, define

$$\widehat{f}(y) = \int_{\mathbb{R}^n} e^{-2\pi i(x \cdot y)} dx : \mathbb{R}^n \rightarrow \mathbb{C}.$$

Fact. If f is smooth and rapidly decreasing, so is \widehat{f} .

Fact. If $f(x) = e^{-\pi(x \cdot x)}$, then $\widehat{f}(x) = f(x)$.

Fact. If f is smooth and rapidly decreasing, and \mathbb{R}^n is a lattice with volume V , then

$$\sum_{x \in L} f(x) = \frac{1}{V} \sum_{x \in L^\vee} \widehat{f}(x).$$

1.4.3 Theta series

A crucial assumption is that L is self-dual. An assumption that can be removed is that L is even, so for all $x \in L$, $Q_L(x) \in 2\mathbb{Z}$.

Definition 1.4.6. The **theta series** Θ_L is defined by

$$\Theta_L(z) = \sum_{x \in L} q^{\frac{1}{2}x \cdot x} = \sum_{m=0}^{\infty} a_m q^m, \quad a_m = \# \{x \in \mathbb{Z}^n \mid Q_L(x) = 2m\}.$$

Theorem 1.4.7. Θ_L is modular of weight $n/2$.

Example. Let $\Gamma_8 \subseteq \mathbb{R}^8$ be spanned by

$$\begin{aligned} e_1 &= \left(\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2} \right), & e_2 &= (1, 1, 0, 0, 0, 0, 0, 0), \\ e_3 &= (1, -1, 0, 0, 0, 0, 0, 0), & e_4 &= (0, 1, -1, 0, 0, 0, 0, 0), & e_5 &= (0, 0, 1, -1, 0, 0, 0, 0), \\ e_6 &= (0, 0, 0, 1, -1, 0, 0, 0), & e_7 &= (0, 0, 0, 0, 1, -1, 0, 0), & e_8 &= (0, 0, 0, 0, 0, 1, -1, 0). \end{aligned}$$

Then

$$A = \begin{pmatrix} 2 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & -1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 2 & -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & -1 & 2 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 2 \end{pmatrix},$$

and

$$Q_L(z_1, \dots, z_8) = 2(z_1^2 + \dots + z_8^2 - z_1 z_3 - z_2 z_4 - z_3 z_4 - z_4 z_5 - z_6 z_7 - z_7 z_8).$$

If $L \subseteq \mathbb{R}^n$ is even and self-dual, and Θ_L is modular of weight $n/2$, then dimension is ~ 24 .

Fact. $L \subseteq \mathbb{R}^n$ even and self-dual implies that $8 \mid n$.

Proof. Serre V.2.1 Corollary 2. □

Proof of Theorem 1.4.7. Know, since L is even, that $\Theta_L(z+1) = \Theta_L(z)$. It suffices to show $\Theta_L(-1/z) = z^{n/2}\Theta_L(z)$. Both sides are holomorphic on \mathbb{H} , so it suffices to show

$$\Theta_L\left(-\frac{1}{it}\right) = (it)^{\frac{n}{2}} \Theta_L(it).$$

For $t \in \mathbb{R}^\times$, let $L_t = t^{1/2} \cdot L$ and $L_t^\vee = t^{-1/2} \cdot L = L_{t^{-1}}$, so $\text{vol } L_t = t^{n/2}$. By the facts,

$$\sum_{x \in L_t} e^{-\pi(x \cdot x)} = t^{-\frac{n}{2}} \sum_{x \in L_{t^{-1}}} e^{-\pi(x \cdot x)},$$

so

$$\sum_{x \in L} e^{-\pi(x \cdot x)t} = t^{-\frac{n}{2}} \sum_{x \in L} e^{-\frac{\pi(x \cdot x)}{t}}.$$

Now return to Θ_L . The left hand side is

$$\Theta_L\left(-\frac{1}{it}\right) = \sum_{x \in L} e^{\frac{1}{2} \cdot 2\pi i \cdot \left(-\frac{1}{it}\right) \cdot (x \cdot x)} = \sum_{x \in L} e^{-\frac{\pi(x \cdot x)}{t}},$$

and the right hand side is

$$\Theta_L(it) = \sum_{x \in L} e^{\frac{1}{2} \cdot 2\pi i \cdot (it) \cdot (x \cdot x)} = \sum_{x \in L} e^{\pi(x \cdot x)t},$$

so the result follows. \square

1.4.4 Asymptotic analysis

Let $\Theta_L = \sum_{m=1}^{\infty} a_m q^m$, where a_m is the number of ways Q_L represents $2m$, so $a_0 = 1$. Then

$$\Theta_L = E_{\frac{n}{2}} + g, \quad E_{\frac{n}{2}} \sim \sigma_{\frac{n}{2}-1}(m) \sim m^{\frac{n}{2}-1},$$

where g is a cusp form.

Lecture 12 is a problem class.

Proposition 1.4.8. *Let*

$$E_k = \sum_{n=0}^{\infty} a_n q^n = 1 + C \sum_{n=1}^{\infty} \sigma_{k-1}(n) q^n.$$

Then there exist $A, B \in \mathbb{R}_{>0}$ such that

$$An^{k-1} \leq a_n \leq Bn^{k-1}.$$

Proof. Set $A = C$. Then

$$\sigma_{k-1}(n) = \sum_{d|n} d^{k-1} \geq n^{k-1},$$

so $a_n = C\sigma_{k-1}(n) \geq Cn^{k-1}$. Consider

$$\frac{\sigma_{k-1}(n)}{n^{k-1}} = \sum_{d|n} \frac{d^{k-1}}{n^{k-1}} = \sum_{d'|n} \frac{1}{d'^{k-1}} \leq \sum_{n=1}^{\infty} \frac{1}{n^{k-1}} = \zeta(k-1),$$

so $\sigma_{k-1}(n) \leq \zeta(k-1)n^{k-1}$. So set $B = C \cdot \zeta(k-1)$, so $a_n \leq Bn^{k-1}$. \square

Theorem 1.4.9 (Hasse). *Let $f = \sum_{n=1}^{\infty} a_n q^n$ be a cusp form of weight k . Then*

$$|a_n| = O\left(n^{\frac{k}{2}}\right),$$

that is $|a_n|n^{-k/2}$ is bounded as $n \rightarrow \infty$.

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Proof. f/q is holomorphic on \mathbb{H} , so $|f/q|$ is bounded as $q \rightarrow 0$, so $|f(z)|/e^{-2\pi \operatorname{Im} z}$ is bounded as $\operatorname{Im} z \rightarrow \infty$. That is, there exist $M \in \mathbb{R}$ such that $|f(z)| \leq M e^{-2\pi \operatorname{Im} z}$. Consider

$$\phi(z) = |f(z)| \operatorname{Im} z^{\frac{k}{2}},$$

so $\lim_{\operatorname{Im} z \rightarrow \infty} \phi(z) = 0$. Note that

$$\phi(\gamma z) = |f(\gamma z)| \operatorname{Im} \gamma z^{\frac{k}{2}} = |f(z)| |cz + d|^k \frac{\operatorname{Im} z^{\frac{k}{2}}}{|cz + d|^{2\frac{k}{2}}} = |f(z)| \operatorname{Im} z^{\frac{k}{2}} = \phi(z), \quad \gamma \in \operatorname{SL}_2(\mathbb{Z}).$$

Then $\phi(z)$ is determined by its values on the standard fundamental domain, so $\phi(z)$ is bounded on \mathbb{H} , so $|f(z)| < M' \operatorname{Im} z^{-k/2}$ for some $M' \in \mathbb{R}$. If $z = x + iy$ for y fixed, then the residue theorem implies that

$$a_m = \frac{1}{2\pi i} \int_C \frac{f(q)}{q^{m+1}} dq = \int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{f(x + iy)}{e^{2\pi i(x+iy)m}} dx,$$

so

$$|a_m| \leq \int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{|f(x + iy)|}{e^{-2\pi ym}} dx \leq \frac{|f(x + iy)|}{e^{-2\pi ym}} \leq e^{2\pi ym} M' y^{-\frac{k}{2}}.$$

Set $y = 1/m$. Get $|a_n| \leq e^{2\pi} M' m^{k/2}$, so $|a_m|/m^{k/2}$ is bounded. \square

Had

$$\Theta_L = E_{\frac{n}{2}} + g, \quad E_{\frac{n}{2}} \sim m^{\frac{n}{2}-1}, \quad g = O\left(m^{\frac{n}{4}}\right).$$

Theorem 1.4.10 (Deligne). *Let $f = \sum_{n=1}^{\infty} a_n q^n$ be a cusp form of weight k . Then*

$$|a_n| = O\left(n^{\frac{k-1}{2}} \sigma_0(n)\right).$$

Proof. Very rough sketch of argument.

Ramanujan 1910s. Conjectured by Ramanujan for $f = \Delta$.

Weil 1940s. For an algebraic variety V over \mathbb{F}_q , what can we say about $\#V(\mathbb{F}_{q^n})$ for various n ? Weil associated to V and \mathbb{F}_q a generating function called the **zeta function** $\zeta_{V,q}(t)$ of V over \mathbb{F}_q , conjectured several things about $\zeta_{V,q}$, and proved in the case of curves.

- $\zeta_{V,q}$ is a rational function in t .
- $\zeta_{V,q}$ satisfies a certain symmetry under $t \mapsto 1/t$.
- The Riemann hypothesis

$$\zeta_{V,q}(t) = \frac{P_1(t) \dots P_{2d-1}(t)}{P_0(t) \dots P_{2d}(t)}, \quad \dim V = d,$$

where the roots of $P_i(t)$ have absolute value $q^{i/2}$.

Eichler-Shimura 1950s. Let $\Gamma \subseteq \operatorname{SL}_2(\mathbb{Z})$ be a nice **congruence subgroup**. Then $X_\Gamma = \Gamma \backslash \mathbb{H}$ has the structure of an algebraic curve over \mathbb{Q} , with **good reduction** at primes p not dividing $[\operatorname{SL}_2(\mathbb{Z}) : \Gamma]$. Eichler, Shimura, and others studied $\zeta_{V,p}$ for $V = X_\Gamma$, and related $\zeta_{V,p}$ to the p -th Fourier coefficients of a basis for forms of weight two and **level** Γ . The Weil conjectures bound a_p in terms of $q^{1/2}$.

Deligne 1960s. Deligne showed that in weight k , there exists a **Kuga-Sato variety**, of dimension $k - 1$, whose zeta function has a factor coming from modular forms of weight k and level Γ , and showed that if the Weil conjectures, particularly the Riemann hypothesis, holds, then get the coefficient bound.

Deligne 1970s. Riemann hypothesis in higher dimensions. \square

1.5 Hecke operators

Let $\Delta = (E_4^3 - E_6^2) / 1728 = \sum_{n=1}^{\infty} \tau(n) q^n$. Then $\tau(n)$ grows roughly like n^6 or $n^{11/2+\epsilon}$. Mordell proved

- $\tau(mn) = \tau(n) \tau(m)$ if $(m, n) = 1$, and
- $\tau(p^{n+1}) = \tau(p) \tau(p^n) - p^{11} \tau(p^{n-1})$.

If $E_k = 1 + C \sum_n \sigma_{k-1}(n) q^n$, set

$$E'_k = \frac{1}{C} + \sum_n \sigma_{k-1}(n) q^n.$$

Note.

- If $(m, n) = 1$, then

$$\sigma_{k-1}(nm) = \sum_{d|n} \sum_{d'|m} (dd')^{k-1} = \left(\sum_{d|n} d^{k-1} \right) \left(\sum_{d'|m} d'^{k-1} \right) = \sigma_{k-1}(n) \sigma_{k-1}(m).$$

- Since $\sigma_{k-1}(p^n) = 1 + \dots + p^{n(k-1)}$,

$$\begin{aligned} \sigma_{k-1}(p) \sigma_{k-1}(p^n) &= (1 + p^{k-1}) (1 + \dots + p^{n(k-1)}) \\ &= 1 + 2p^{k-1} + \dots + 2p^{n(k-1)} + p^{(n+1)(k-1)} \\ &= \sigma_{k-1}(p^{n+1}) + p^{k-1} \sigma_{k-1}(p^{n-1}), \end{aligned}$$

so

$$\sigma_{k-1}(p^{n+1}) = \sigma_{k-1}(p) \sigma_{k-1}(p^n) - p^{k-1} \sigma_{k-1}(p^{n-1}).$$

1.5.1 Correspondences

Definition 1.5.1. Let X be a set. The **free abelian group on X** , denoted $\mathbb{Z}X$, is the set of finite formal sums

$$\sum_{i=1}^r a_i x_i, \quad a_i \in \mathbb{Z}, \quad x_i \in X,$$

where x_i are distinct. Add by combining like terms.

Definition 1.5.2. A **correspondence** on X is a homomorphism $\mathbb{Z}X \rightarrow \mathbb{Z}X$. Let

$$\text{Corr } X = \{\text{correspondences on } X\}.$$

Equivalently, a correspondence associates to each $x \in X$, a finite formal sum

$$\sum_{i=1}^r a_i y_i, \quad a_i \in \mathbb{Z}, \quad y_i \in X.$$

If X is a finite set $X = \{x_1, \dots, x_r\}$, any correspondence T can be represented, in a unique way, by the matrix M_T such that

$$Tx_i = \sum_{j=1}^r (M_T)_{ij} x_j,$$

and composition of correspondences is matrix multiplication. Let X be a set, and let

$$\text{Fun}_{\mathbb{C}} X = \{\text{functions } X \rightarrow \mathbb{C}\}.$$

Then $T \in \text{Corr } X$ acts on $\text{Fun}_{\mathbb{C}} X$ as follows. If $Tx = \sum_i a_i x_i$ then $(Tf)x = \sum_i a_i f(x_i)$. Check $(T \circ T')f = T(T'f)$, etc. Let

$$\mathcal{L} = \{\text{lattices in } \mathbb{C}\}.$$

Example. The following are correspondences in \mathcal{L} .

- For $\lambda \in \mathbb{C}^\times$, have

$$\begin{array}{ccc} R_\lambda & : & \mathbb{Z}\mathcal{L} \longrightarrow \mathbb{Z}\mathcal{L} \\ & & L \longmapsto \lambda L \end{array}.$$

- For $n \in \mathbb{Z}_{>0}$, have

$$\begin{array}{ccc} T_n & : & \mathbb{Z}\mathcal{L} \longrightarrow \mathbb{Z}\mathcal{L} \\ & & L \longmapsto \sum_{L' \subseteq_n L} L' \end{array},$$

the n **Hecke operators**. Note that there are only finitely many $L' \subseteq L$ of index n , since if L' has index n in L , then L' contains $R_n L$. Then $L/R_n L \cong \mathbb{Z}/n\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z}$. The image of L' in $L/R_n L$ is a subgroup H of $\mathbb{Z}/n\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z}$ of order n . The preimage of H in L is L' . Thus there is a bijection

$$\{ \text{subgroups of } L/R_n L \text{ of order } n \} \longleftrightarrow \{ \text{sublattices of index } n \}.$$

Proposition 1.5.3.

1. $R_\lambda R_\mu = R_{\lambda\mu}$.
2. $R_\lambda T_n = T_n R_\lambda$.
3. $T_n T_m = T_{nm}$ if $(m, n) = 1$.
4. $T_p T_{p^n} = T_{p^{n+1}} + p T_{p^{n+1}} R_p$.

Corollary 1.5.4. T_p commute with each other for p prime, also with R_λ , and every T_n is a polynomial in T_p and R_p for $p \mid n$, so all T_n and R_λ commute.

Proposition 1.5.5. If A is an abelian group of order nm , with $(n, m) = 1$, then A factors uniquely as $B \times C$, where B has order n and C has order m . In particular B is the unique subgroup of A of order n .

Proof. Write $1 = an + bm$ for $a, b \in \mathbb{Z}$. Have a map

$$\begin{array}{ccc} A & \longleftrightarrow & mA \times nA \\ x & \longmapsto & (mbx, nax) \\ x + y & \longmapsto & (x, y) \end{array}$$

Then mA has order n and nA has order m . Clearly inverses on one side, so counting implies isomorphism. \square

Proof of Proposition 1.5.3.

1. Easy.
2. If $L \in \mathcal{L}$, then

$$R_\lambda T_n L = R_\lambda \sum_{L' \subseteq_n L} L' = \sum_{L' \subseteq_n L} R_\lambda L' = \sum_{L' \subseteq_n R_\lambda L} L' = T_n R_\lambda L.$$

3. If $L \in \mathcal{L}$, then

$$T_n T_m L = T_n \sum_{L' \subseteq_m L} L' = \sum_{L' \subseteq_m L} T_n L' = \sum_{L' \subseteq_m L} \sum_{L'' \subseteq_n L'} L''.$$

An observation is $L'' \subseteq_n L' \subseteq_m L$, so L'' has index nm in L . Let

$$T_n T_m L = \sum_{L'' \subseteq_{nm} L} c_{n,m}(L'', L) L'', \quad c_{n,m}(L'', L) = \# \{ L' \in \mathcal{L} \mid L'' \subseteq_n L' \subseteq_m L \}.$$

An observation is that there is a bijection

$$\begin{array}{ccc} \{ \text{lattices } L' \mid L'' \subseteq_n L' \subseteq_m L \} & \longleftrightarrow & \{ \text{subgroups } H \text{ of } L/L'' \text{ of order } n \} \\ L' & \longmapsto & L'/L'' \subseteq L/L'' \\ \text{preimage of } H \text{ under } L \rightarrow L/L'' & \longleftarrow & H \end{array}.$$

Have $(n, m) = 1$, so $c_{n,m}(L'', L) = 1$ so

$$T_n T_m L = \sum_{L'' \subseteq_{nm} L} c_{n,m}(L'', L) L'' = \sum_{L'' \subseteq_{nm} L} L'' = T_{nm} L.$$

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4. If $L \in \mathcal{L}$, then

$$T_p T_{p^r} L = \sum_{L'' \subseteq_{p^{r+1}} L} c_{p,p^r}(L'', L) L'', \quad c_{p,p^r}(L'', L) = \#\{L' \in \mathcal{L} \mid L'' \subseteq_p L' \subseteq_{p^r} L\}.$$

What is

$$c_{p,p^r}(L'', L) = \#\{\text{subgroups of order } p \text{ in } L/L''\}?$$

L/L'' is abelian of order p^{r+1} and generated by two elements. The classification of finite abelian groups implies that every finite abelian group can be written uniquely as $\mathbb{Z}/a_1\mathbb{Z} \times \cdots \times \mathbb{Z}/a_r\mathbb{Z}$ where $a_1 \mid \cdots \mid a_r$, up to isomorphism, and r is the minimal number of generators for such a group. So

$$L/L'' \cong \mathbb{Z}/p^a\mathbb{Z} \times \mathbb{Z}/p^b\mathbb{Z}, \quad a, b \geq 0, \quad a + b = r + 1.$$

Case 1. $L/L'' \cong \mathbb{Z}/p^{r+1}\mathbb{Z}$ is cyclic. In this case $c_{p,p^r}(L'', L) = 1$.

Case 2. $L/L'' \cong \mathbb{Z}/p^a\mathbb{Z} \times \mathbb{Z}/p^b\mathbb{Z}$ with $a, b > 0$. Any subgroup of order p is contained in the subgroup killed by p ,

$$p^{a-1}\mathbb{Z}/p^a\mathbb{Z} \times p^{b-1}\mathbb{Z}/p^b\mathbb{Z} \cong (\mathbb{Z}/p\mathbb{Z})^2.$$

The $p^2 - 1$ elements of $(\mathbb{Z}/p\mathbb{Z})^2 \setminus \{0\}$ each spans a subgroup of order p , and two elements span the same group if and only if they differ by a scalar in $(\mathbb{Z}/p\mathbb{Z})^\times$, so there are $(p^2 - 1) / (p - 1) = p + 1$ subgroups of order p in $(\mathbb{Z}/p\mathbb{Z})^2$. In this case $c_{p,p^r}(L'', L) = p + 1$.

The latter case occurs if and only if L/L'' maps surjectively to $(\mathbb{Z}/p\mathbb{Z})^2 \cong L/R_p L$, if and only if $R_p L \supseteq L''$. Thus

$$\begin{aligned} T_p T_{p^r} L &= \sum_{L'' \subseteq_{p^{r+1}} L} c_{p,p^r}(L'', L) L'' = \sum_{L'' \subseteq_{p^{r+1}} L \text{ cyclic}} L'' + \sum_{L'' \subseteq_{p^{r+1}} L \text{ not cyclic}} (p + 1) L'' \\ &= T_{p^{r+1}} L + p \sum_{L'' \subseteq_{p^{r+1}} L \text{ not cyclic}} L'' = T_{p^{r+1}} L + p \sum_{L'' \subseteq_{p^{r-1}} R_p L} L'' = T_{p^{r+1}} L + p T_{p^{r-1}} R_p L. \end{aligned}$$

□

1.5.2 Hecke operators

If $F : \mathcal{L} \rightarrow \mathbb{C}$, then

$$T_n F(L) = \sum_{L' \subseteq_n L} F(L'), \quad R_\lambda F(L) = F(R_\lambda L).$$

Recall that F has weight k if $F(R_\lambda L) = \lambda^{-k} F(L)$ for all $\lambda \in \mathbb{C}^\times$, if and only if $R_\lambda F = \lambda^{-k} F$ for all $\lambda \in \mathbb{C}^\times$, so

$$R_\lambda T_n F = T_n R_\lambda F = T_n \lambda^{-k} F = \lambda^{-k} T_n F.$$

So the T_n and R_λ preserve lattice functions of weight k . Have a bijection

$$\begin{aligned} \left\{ f : \mathbb{H} \rightarrow \mathbb{C} \mid f(\gamma z) = (cz + d)^k f(z) \right\} &\longrightarrow \{\text{lattice functions } F \text{ of weight } k\} \\ f(z) &\longmapsto F(L_{z,1}) \end{aligned}$$

On lattice functions of weight k , have

$$T_p T_{p^r} = T_{p^{r+1}} + p^{1-k} T_{p^{r-1}}.$$

Definition 1.5.6. For $f : \mathbb{H} \rightarrow \mathbb{C}$ corresponding to $F : \mathcal{L} \rightarrow \mathbb{C}$ of weight k , define $T_n f$ by

$$(T_n f)(z) = n^{k-1} (T_n F)(L_{z,1}) = n^{k-1} \sum_{L' \subseteq_n L_{z,1}} F(L').$$

On $f : \mathbb{H} \rightarrow \mathbb{C}$, T_n satisfy

$$T_p T_{p^r} = T_{p^{r+1}} + p^{k-1} T_{p^{r-1}}.$$

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Need to rewrite $\sum_{L' \subseteq_n L_{z,1}} F(L')$ in terms of f . Let

$$S_n = \left\{ \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \in \text{Mat}_{2 \times 2} \mathbb{Z} \mid ad = n, a, d > 0, 0 \leq b < d \right\}, \quad s_n = \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \in S_n.$$

Lemma 1.5.7. *The map*

$$\begin{aligned} S_n &\longrightarrow \{ \text{sublattices of } L_{z,1} \text{ of index } n \} \\ \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} &\longmapsto L_{az+b,d} \end{aligned}$$

is a bijection.

Proof. For surjectivity, let $L \subseteq_n L_{z,1}$. Then $L_{z,1}/L$ is a group of order n . Can consider $1 + L \in L_{z,1}/L$. Let d be the order of $1 + L$, that is d is the smallest positive integer such that $d \in L$. Then $d \mid n$, so set $a = n/d$. Let $L' = \mathbb{Z} + L$ be the lattice generated by 1 and L . Then $L \subseteq_d L'$ and $L \subseteq_n L_{z,1}$, so $L' \subseteq_a L_{z,1}$, so $az \in L'$, so there exists $b \in \mathbb{Z}$ such that $az + b \in L$. Since $d \in L$, without loss of generality can arrange $0 \leq b < d$. Now $d \in L$ and $az + b \in L$, so $L \subseteq_n L_{z,1}$ and $L_{az+b,d} \subseteq_n L_{z,1}$, so $L = L_{az+b,d}$. Thus surjective, and for injectivity, can recover a, b, d from $L_{az+b,d} \subseteq L_{z,1}$. \square

Thus

$$\begin{aligned} T_n f &= n^{k-1} \sum_{L' \subseteq_n L_{z,1}} F(L') = n^{k-1} \sum_{s_n \in S_n} F(L_{az+b,d}) \\ &= n^{k-1} \sum_{s_n \in S_n} d^{-k} F\left(L_{\frac{az+b}{d},1}\right) = n^{k-1} \sum_{s_n \in S_n} d^{-k} f\left(\frac{az+b}{d}\right). \end{aligned}$$

Theorem 1.5.8. *If $f = \sum_{m=0}^{\infty} c(m) q^m$ is modular of weight k , then*

$$T_n f = \sum_{m=0}^{\infty} \gamma(m) q^m, \quad \gamma(m) = \sum_{a \mid (m,n), a \geq 1} d^{k-1} c\left(\frac{mn}{a^2}\right).$$

Proof.

$$\begin{aligned} T_n f &= n^{k-1} \sum_{s_n \in S_n} d^{-k} f\left(\frac{az+b}{d}\right) = n^{k-1} \sum_{s_n \in S_n} \sum_{m=0}^{\infty} d^{-k} c(m) e^{2\pi i m \left(\frac{az+b}{d}\right)} \\ &= n^{k-1} \sum_{ad=n, a>0} \sum_{b=0}^{d-1} \sum_{m=0}^{\infty} d^{-k} c(m) q^{\frac{ma}{d}} e^{\frac{2\pi i mb}{d}} = n^{k-1} \sum_{m=0}^{\infty} \sum_{ad=n, a>0} d^{-k} c(m) q^{\frac{ma}{d}} \sum_{b=0}^{d-1} e^{\frac{2\pi i mb}{d}}. \end{aligned}$$

Then

$$\sum_{b=0}^{d-1} e^{\frac{2\pi i mb}{d}} = \begin{cases} d & d \mid m \\ 0 & d \nmid m \end{cases},$$

so

$$T_n f = n^{k-1} \sum_{m=0}^{\infty} \sum_{d \mid m, ad=n, a>0} d^{1-k} c(m) q^{\frac{ma}{d}} = \sum_{a \mid n, a>0} \sum_{m'=0}^{\infty} a^{k-1} c\left(\frac{m'n}{a}\right) q^{m'a}.$$

Which m' and a give q^m ? Need $a \mid (m,n)$ for $a > 0$ and $m'a = m$, so the coefficient is $a^{k-1} c(mn/a^2)$. The sum of these is $\gamma(m)$. \square

Corollary 1.5.9. T_n preserves M_k and S_k .

In the case $n = p$,

$$T_p f = \sum_{m=0}^{\infty} \gamma(m) q^m, \quad \gamma(m) = \begin{cases} c(mp) + p^{k-1} c\left(\frac{m}{p}\right) & p \mid m \\ c(mp) & p \nmid m \end{cases}.$$

1.5.3 Eigenforms

An observation is that the dimensions of $M_4, M_6, M_8, M_{10}, S_{12}$ are one, so $E_4, E_6, E_8, E_{10}, \Delta$ are eigenvectors for T_n for all n .

Definition 1.5.10. A function $f \in M_k$ is an **eigenform** if there exists $\lambda_n \in \mathbb{C}^\times$ such that $T_n f = \lambda_n f$ for all $n \in \mathbb{Z}_{>0}$.

Proposition 1.5.11. Let $f \in M_k$ be an eigenform, with $k > 0$, so $T_n f = \lambda_n f$ for all n . Then if $f = \sum_m c_m q^m$, we have $c_1 \neq 0$ and $\lambda_n c_1 = c_n$ for all $n \geq 1$. In particular, if $c_1 = 1$, then $c_n = \lambda_n$ for all n .

Proof.

$$\sum_{m=0}^{\infty} \lambda_n c_m q^m = \lambda_n f = T_n f = \sum_{m=0}^{\infty} \gamma(m) q^m, \quad \gamma(1) = \sum_{a|(1,n)} a^{k-1} c(n) = c(n),$$

so $\lambda_n c_1 = c_n$. Suppose $c_1 = 0$. Then $c_n = 0$ for all $n \geq 1$, so f is constant. Since $k \neq 0$, this does not happen. \square

Corollary 1.5.12. Recall $\Delta(z) = \sum_n \tau(n) q^n$. Then

- $\tau(mn) = \tau(n) \tau(m)$ if $(m, n) = 1$, and
- $\tau(p^{r+1}) = \tau(p) \tau(p^r) - p^{11} \tau(p^{r-1})$.

Proof. $\Delta \in S_{12}$ is one-dimensional, so there exists λ_n such that $T_n \Delta = \lambda_n \Delta$. Proposition 1.5.11 implies that $\lambda_n = \tau(n)$ for all n . Thus

- $\tau(mn) \Delta = \lambda_{mn} \Delta = T_{mn} \Delta = T_m T_n \Delta = \lambda_m \lambda_n \Delta = \tau(m) \tau(n) \Delta$, and
- $\tau(p^{r+1}) \Delta = T_{p^{r+1}} \Delta = T_p T_{p^r} \Delta - p^{11} T_{p^{r-1}} \Delta = (\tau(p) \tau(p^r) - p^{11} \tau(p^{r-1})) \Delta$.

\square

In fact, the same argument shows if $f \in M_k$ for $k > 0$ is an eigenform, with q -coefficient one, a **normalised eigenform**, and $f = \sum_{n=0}^{\infty} c_n q^n$, then

- $c_{nm} = c_n c_m$ if $(n, m) = 1$, and
- $c_{p^{r+1}} = c_p c_{p^r} - p^{k-1} c_{p^{r-1}}$.

Proposition 1.5.13. E_k is an eigenform for all k .

Proof. It suffices to show $T_p E_k = \lambda_p E_k$ for all primes p . Recall E_k is a constant multiple of G_k , where $G_k(L) = \sum_{w \in L, w \neq 0} 1/w^k$. Now

$$(T_p f)(L) = \sum_{L' \subseteq_p L} \sum_{w \in L', w \neq 0} \frac{1}{w^k} = \sum_{w \in L, w \neq 0} c_w \frac{1}{w^k}, \quad c_w = \# \{L' \subseteq_p L \mid w \in L'\}.$$

Note that $pL \subseteq L' \subseteq L$. If $w \in pL$, then $w \in L'$ for all $L' \subseteq_p L$, and there are $p+1$ of these. If $w \notin pL$, then $pL \subseteq_{p^2} L$ and $pL \subsetneq pL + \mathbb{Z}w \subsetneq L$, so $pL \subsetneq_p pL + \mathbb{Z}w$ and $pL + \mathbb{Z}w \subsetneq_p L$. In this case there exists a unique lattice of index p containing w . Thus

$$\begin{aligned} T_p G_k(L) &= \sum_{w \in L \setminus pL} \frac{1}{w^k} + \sum_{w \in pL, w \neq 0} (p+1) \frac{1}{w^k} = \sum_{w \in L, w \neq 0} \frac{1}{w^k} + p \sum_{w \in pL, w \neq 0} \frac{1}{w^k} \\ &= G_k(L) + p \sum_{w \in L, w \neq 0} \frac{1}{(pw)^k} = G_k(L) + p^{1-k} \sum_{w \in L} \frac{1}{w^k} = (1 + p^{1-k}) G_k(L), \end{aligned}$$

so $T_p E_k = (1 + p^{k-1}) E_k$. \square

A question is does M_k have a basis of eigenforms for all k ? By linear algebra, there exist nice classes of operators that are guaranteed to admit bases of eigenvectors, such as self-adjoint, or more generally, normal operators.

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1.5.4 Hermitian pairings

Let V be a \mathbb{C} -vector space and $\langle -, - \rangle : V \times V \rightarrow \mathbb{C}$ a **Hermitian pairing**. That is,

- $\langle \lambda v + w, x \rangle = \lambda \langle v, x \rangle + \langle w, x \rangle$,
- $\langle x, y \rangle = \overline{\langle y, x \rangle}$, and
- $\langle x, x \rangle > 0$ for all $x \neq 0$.

Example. The standard pairing

$$\begin{aligned} \mathbb{C}^n \times \mathbb{C}^n &\longrightarrow \mathbb{C} \\ \langle z, w \rangle &\longmapsto \sum_{i=1}^n z_i \overline{w_i} . \end{aligned}$$

Definition 1.5.14. Let $A : V \rightarrow V$ be \mathbb{C} -linear, and $\langle -, - \rangle : V \times V \rightarrow \mathbb{C}$ Hermitian. Then the **adjoint** $A^* : V \rightarrow V$ is the unique linear map $V \rightarrow V$ such that

$$\langle Av, w \rangle = \langle v, A^*w \rangle .$$

We say A is **self-adjoint** if $A^* = A$, and **normal** if A^* commutes with A .

Theorem 1.5.15. *If A is normal, then A has a basis of eigenvectors.*

Lemma 1.5.16. $A^{**} = A$.

Proof. For all $v, w \in V$,

$$\langle v, A^{**}w \rangle = \langle A^*v, w \rangle = \overline{\langle w, A^*v \rangle} = \overline{\langle Aw, v \rangle} = \langle v, Aw \rangle ,$$

so $A^{**}w = Aw$ for all $w \in V$. □

Definition 1.5.17. If $W \subseteq V$, let

$$W^\perp = \{v \in V \mid \forall w \in W, \langle v, w \rangle = 0\} .$$

Proposition 1.5.18. $\text{Im } A^* = (\text{Ker } A)^\perp$.

Proof. $\langle v, A^*w \rangle = \langle Av, w \rangle = 0$ if $v \in \text{Ker } A$. So $\text{Im } A^* \subseteq (\text{Ker } A)^\perp$, so $\text{rk } A^* \leq \text{rk } A$. The same argument with A^* in place of A implies that $\text{rk } A = \text{rk } A^{**} \leq \text{rk } A^*$. So $\text{rk } A^* = \text{rk } A$, so $\text{Im } A^* = (\text{Ker } A)^\perp$. □

In particular, $\text{Im } A^* \cap \text{Ker } A = \{0\}$ and $\dim \text{Im } A^* + \dim \text{Ker } A = \text{rk } A^* + n - \text{rk } A = n$. So $V = \text{Im } A^* \oplus \text{Ker } A$.

Theorem 1.5.19 (Spectral theorem for normal operators). *If A and A^* commute, then A^* is diagonalisable.*

Proof. Induction on $\dim V$. Then $\dim V = 1$ is clear. Let λ be an eigenvalue of A , and let $A' = A - \lambda I_V$, so $V = \text{Ker } A' \oplus \text{Im } A'^*$, where $\dim \text{Ker } A' > 0$. Then A commutes with A' , and $A'^* = A^* - \overline{\lambda} I_V$, so A commutes with A'^* . So $AA'^*v = A'^*Av$, so A preserves the image of A'^* . The restriction of $\langle -, - \rangle$ to $\text{Im } A'^*$ is still Hermitian on $\text{Im } A'^*$ and the restriction of A to $\text{Im } A'^*$ is still normal, since its adjoint is the restriction of A^* to $\text{Im } A'^*$. By induction A is diagonalisable on $\text{Im } A'^*$ and scalar on $\text{Ker } A'$, so diagonalisable. □

Also the need the following observation.

Proposition 1.5.20. *If $A : V \rightarrow V$ and $B : V \rightarrow V$ commute, and $V_\lambda = \text{Ker } (A - \lambda I_V)$, then $BV_\lambda = V_\lambda$.*

Proof. If $v \in V_\lambda$, then $ABv = BAv = B\lambda v = \lambda Bv$, so $Bv \in V_\lambda$. □

1.5.5 The Petersson inner product

To apply this to modular forms, we need a bilinear pairing on M_k or S_k . The idea is to show that there exists a pairing $\langle -, - \rangle_k : S_k \times S_k \rightarrow \mathbb{C}$ such that $\langle T_n f, g \rangle = \langle f, T_n g \rangle$ for all n , so T_n are self-adjoint, hence diagonalisable.

Definition 1.5.21. Let $f, g \in S_k$. The **Petersson inner product** $\langle f, g \rangle_k$ is

$$\langle f, g \rangle_k = \iint_{\mathcal{D}} f(z) \overline{g(z)} \frac{(\text{Im } z)^k}{(\text{Im } z)^2} dx dy = \frac{i}{2} \iint_{\mathcal{D}} f(z) \overline{g(z)} \frac{(\text{Im } z)^k}{(\text{Im } z)^2} dz d\bar{z} .$$

Here $z = x + iy$ and $\bar{z} = x - iy$, so $dz d\bar{z} = (dx + idy) \wedge (dx - idy) = -2i(dx \wedge dy)$.

Then

$$f(\gamma z) \overline{g(\gamma z)} (\operatorname{Im} \gamma z)^k = f(z) (cz + d)^k \overline{g(z) (cz + d)^k} \frac{\operatorname{Im} z}{|cz + d|^{2k}} = f(z) \overline{g(z)} (\operatorname{Im} z)^k,$$

and

$$\frac{1}{(\operatorname{Im} \gamma z)^2} d(\gamma z) (\gamma \bar{z}) = \frac{1}{(\operatorname{Im} \gamma z)^2 |cz + d|^4} dz d\bar{z} = \frac{1}{(\operatorname{Im} z)^2} dz d\bar{z},$$

so for all $U \subseteq \mathbb{H}$,

$$\iint_{\gamma(U)} f(z) \overline{g(z)} \frac{(\operatorname{Im} z)^k}{(\operatorname{Im} z)^2} dz d\bar{z} = \iint_U f(z) \overline{g(z)} \frac{(\operatorname{Im} z)^k}{(\operatorname{Im} z)^2} dz d\bar{z}.$$

Note. This converges for $f, g \in S_k$, since $f(a + it)$ goes like e^{-t} as $t \rightarrow \pm\infty$, and the same for g . If $\langle f, f \rangle = 0$, the integrand vanishes identically, since it lives in $\mathbb{R}_{\geq 0}$. So $f = 0$ on \mathcal{D} , hence everywhere. Then

$$\langle \lambda f, g \rangle_k = \lambda \langle f, g \rangle_k, \quad \langle f, \lambda g \rangle_k = \bar{\lambda} \langle f, g \rangle_k, \quad \langle f, g \rangle_k = \overline{\langle g, f \rangle_k}.$$

So $\langle -, - \rangle_k$ is Hermitian.

Theorem 1.5.22. $\langle T_n f, g \rangle_k = \langle f, T_n g \rangle_k$ for all $f, g \in S_k$ and $n \in \mathbb{Z}_{\geq 1}$.

Corollary 1.5.23. Each T_n is diagonalisable on S_k . Since T_n and T_m commute for all n and m , T_m preserves eigenspaces of T_n for all m . By induction, T_m preserves the simultaneous eigenspaces of T_n for all $n < m$.

Proposition 1.5.24. Let $n > \lfloor k/12 \rfloor + 1$. Fix $\lambda_2, \dots, \lambda_n \in \mathbb{C}$. The subspace V of S_k on which $T_i = \lambda_i$ for $i = 2, \dots, n$ is zero or one-dimensional.

Proof. Let $f \in V$, so $f = c_1 q + c_2 q^2 + \dots$. Seen if $T_i f = \lambda_i f$, then $c_i = \lambda_i c_1$. Also seen that if the first n Fourier coefficients of f vanishes, then $f = 0$, by the $k/12$ -formula. So $c_1 \neq 0$ unless $f = 0$. Now if $f, g \in V \setminus \{0\}$, there exists $\lambda \in \mathbb{C}$ such that f and λg have the same q -coefficient, and thus the same first n Fourier coefficients. But then $f - \lambda g = 0$. \square

Corollary 1.5.25. S_k admits a basis of eigenforms for all k .

Proof. Let $n \geq \lfloor k/12 \rfloor + 1$. Can diagonalise S_k with respect to the first n Hecke operators. Any simultaneous eigenspace for these is at most one-dimensional, and preserved by all T_n . So each of these is actually an eigenspace for all T_n . \square

Note. If f and g are eigenforms, and f is not a scalar multiple of g , there exists T_n such that $T_n f = \lambda_n f$ and $T_n g = \mu_n g$ with $\lambda_n \neq \mu_n$. Then

$$\langle T_n f, g \rangle_k = \langle \lambda_n f, g \rangle_k = \lambda_n \langle f, g \rangle_k, \quad \langle f, T_n g \rangle_k = \langle f, \mu_n g \rangle_k = \mu_n \langle f, g \rangle_k,$$

$$\lambda_n \langle f, f \rangle_k = \langle T_n f, f \rangle_k = \langle f, T_n f \rangle_k = \overline{\langle T_n f, f \rangle_k} = \bar{\lambda}_n \langle f, f \rangle_k.$$

So $\lambda_n = \bar{\lambda}_n$ and $\mu_n = \bar{\mu}_n$. Then $(\lambda_n - \mu_n) \langle f, g \rangle_k = 0$, so $\langle f, g \rangle_k = 0$.

The formula for T_n on q -expansions implies that T_n takes a q -expansion with \mathbb{Z} coefficients to another such. Saw that the space of modular forms with integral q -expansions is spanned by

$$E_4^n E_6^m, \dots, E_4^{n-3\lfloor n/3 \rfloor} E_6^m \Delta^{\lfloor n/3 \rfloor}, \quad k = 4n + 6m, \quad n, m > 0,$$

where $m \in \{0, 1\}$ is minimal, so the matrix of T_n with respect to this basis has integer entries. Thus the characteristic polynomial of T_n on S_k has integer coefficients, so the eigenvalues of T_n are algebraic integers.

Example. Can ask when modular forms are congruent modulo p . In fact $E_{12} \equiv \Delta \pmod{691}$.

Ribet 1970s proved that when an Eisenstein series of suitable weight is congruent modulo p to a cusp form, can use the Galois representation attached to that cusp form to construct elements of ideal class groups of cyclotomic fields.

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1.6 L-functions

1.6.1 Dirichlet L-functions

Definition 1.6.1. Let $\{a_n\}_{n \geq 1}$ be a sequence of complex numbers, usually algebraic integers. The **Dirichlet series** attached to a_n is the formal series $\sum_{n=1}^{\infty} a_n n^{-s}$, thought of as a function of $s \in \mathbb{C}$.

Example. $\zeta(s) = \sum_{n=1}^{\infty} n^{-s}$.

In general, if $|a_n| \leq Cn^k$, then the corresponding series converges absolutely for $\operatorname{Re} s > k + 1$.

Example. Let $\chi : (\mathbb{Z}/N\mathbb{Z})^\times \rightarrow \mathbb{C}^\times$ be a **primitive character**, that is does not factor through $(\mathbb{Z}/N\mathbb{Z})^\times \rightarrow (\mathbb{Z}/m\mathbb{Z})^\times$ for $m \mid N$ such that $m \neq N$. Set

$$a_n = \begin{cases} \chi(n) & (n, N) = 1 \\ 0 & (n, N) \neq 1 \end{cases}.$$

Then

$$L(s, \chi) = \sum_n a_n n^{-s}$$

is the **Dirichlet L-function** attached to χ .

In both these examples, and many others,

- these series have meromorphic, and often analytic, continuations to all of \mathbb{C} ,
- there is a **functional equation** relating values at s and $k - s$ for some k , and
- there is an **Euler product**.

Example.

$$\zeta(s) = 2^s \pi^{s-1} \sin \frac{\pi s}{2} \Gamma(1-s) \zeta(1-s), \quad \zeta(s) = \prod_{p \text{ prime}} \frac{1}{1-p^{-s}}, \quad L(s, \chi) = \prod_{p \nmid N} \frac{1}{1-\chi(p)p^{-s}}.$$

1.6.2 Hecke L-functions

Let $f = \sum_{n=0}^{\infty} a_n q^n \in M_k$. Define

$$L(s, f) = \sum_{n=1}^{\infty} a_n n^{-s}.$$

Example. Let $f = E'_k = (-1)^{k/2} b_k/2k + \sum_{n=1}^{\infty} \sigma_{k-1}(n) q^n$. Then

$$L(s, f) = \sum_{n=1}^{\infty} \sigma_{k-1}(n) n^{-s} = \prod_{p \text{ prime}} \frac{1}{1 - \sigma_{k-1}(p) p^{-s}} = \prod_{p \text{ prime}} \frac{1}{1 - p^{-s}} \cdot \frac{1}{1 - p^{k-1} p^{-s}} = \zeta(s) \zeta(s - k + 1),$$

since $\sigma_{k-1}(mn) = \sigma_{k-1}(m) \sigma_{k-1}(n)$ for $(m, n) = 1$ and $\sigma_{k-1}(p^r) = 1 + \dots + p^{r(k-1)}$.

Let $f = \sum_{n=1}^{\infty} a_n q^n$ be a cusp form. Recall that Hasse implies that $|a_n| \leq Cn^{k/2}$, so gives absolute convergence of $L(s, f)$ for $\operatorname{Re} s > k/2 + 1$.

Theorem 1.6.2.

1. $L(s, f)$ extends to a holomorphic function on all of \mathbb{C} .
2. Set $R(s, f) = (2\pi)^{-s} \Gamma(s) L(s, f)$. Then

$$R(s, f) = (-1)^{\frac{k}{2}} R(k - s, f).$$

3. If f is a normalised eigenform, then

$$L(s, f) = \prod_{p \text{ prime}} \frac{1}{1 - a_p p^{-s} + p^{k-1} p^{-2s}}.$$

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Definition 1.6.3. The infinite product $\prod_{n=1}^{\infty} (1 + c_n)$ **converges** if $\lim_{N \rightarrow \infty} \prod_{n=1}^N (1 + c_n)$ converges to a non-zero number, if and only if $\sum_{n=1}^{\infty} \log(1 + c_n)$ converges. Then $\prod_{n=1}^{\infty} (1 + c_n)$ **converges absolutely** if $\prod_{n=1}^{\infty} (1 + |c_n|)$ converges.

Lemma 1.6.4. $\prod_{n=1}^{\infty} (1 + c_n)$ converges absolutely if and only if $\sum_{n=1}^{\infty} |c_n|$ converges.

Proof.

$$\sum_{n=1}^N |c_n| \leq \prod_{n=1}^N (1 + |c_n|) \leq \prod_{n=1}^N e^{|c_n|} \leq e^{\sum_{n=1}^N |c_n|}.$$

□

Proof of Theorem 1.6.2. Recall that $\Gamma(s) = \int_0^{\infty} t^{s-1} e^{-t} dt$ is meromorphic on \mathbb{H} , with poles at $\mathbb{Z}_{\leq 0}$ and never zero, and satisfies $\Gamma(s+1) = s\Gamma(s)$ so $\Gamma(n) = (n-1)!$. Substituting $t \mapsto 2\pi nt$ in $\Gamma(s)$,

$$\Gamma(s) = \int_0^{\infty} (2\pi nt)^{s-1} e^{-2\pi nt} (2\pi n) dt = (2\pi n)^s \int_0^{\infty} t^{s-1} e^{-2\pi nt} dt,$$

so

$$L(s, f) = \sum_{n=1}^{\infty} a_n n^{-s} = \sum_{n=1}^{\infty} a_n \frac{(2\pi)^s}{\Gamma(s)} \int_0^{\infty} t^{s-1} e^{-2\pi nt} dt.$$

Then

$$\begin{aligned} R(s, f) &= \frac{\Gamma(s)}{(2\pi)^s} L(s, f) = \sum_{n=1}^{\infty} a_n \int_0^{\infty} t^{s-1} e^{-2\pi nt} dt = \int_0^{\infty} t^{s-1} \sum_{n=1}^{\infty} a_n e^{-2\pi nt} dt = \int_0^{\infty} t^{s-1} f(it) dt \\ &= \int_0^1 t^{s-1} f(it) dt + \int_1^{\infty} t^{s-1} f(it) dt = \int_1^{\infty} \left(\frac{1}{t}\right)^{s-1} f\left(\frac{i}{t}\right) d\left(\frac{1}{t}\right) + \int_1^{\infty} t^{s-1} f(it) dt \\ &= \int_1^{\infty} \left(t^{-s-1} (it)^k f(it) + t^{s-1} f(it)\right) dt = \int_1^{\infty} f(it) \left((-1)^{\frac{k}{2}} t^{k-s-1} + t^{s-1}\right) dt, \end{aligned}$$

1. $R(s, f)$ converges independently of s uniformly for s in a compact subset of \mathbb{C} , so it is holomorphic in s , and extends to a holomorphic function on \mathbb{C} . Then $L(s, f) = (2\pi)^s \Gamma(s)^{-1} R(s, f)$, so $L(s, f)$ is holomorphic since $\Gamma(s)$ is non-vanishing.
2. $R(s, f)$ is symmetric up to a sign under $s \mapsto k - s$, so $R(s, f) = (-1)^{k/2} R(k - s, f)$.
3. Now assume f is a normalised eigenform, so $f = \sum_{n=1}^{\infty} a_n q^n$ with $a_1 = 1$ and $T_n f = a_n f$. Then $a_{nm} = a_n a_m$ if $(n, m) = 1$, so

$$L(s, f) = \sum_n a_n n^{-s} = \prod_p \sum_{k=0}^{\infty} a_{p^k} p^{-ks},$$

a power series in p^{-s} . Fix p , and consider

$$(1 - a_p p^{-s} + p^{k-1} p^{-2s}) \sum_{k=0}^{\infty} a_{p^k} p^{-ks}.$$

The p^0 coefficient is $a_1 = 1$, the p^1 coefficient is $a_p p^{-s} - a_p p^{-s} = 0$, and the p^{r+1} coefficient is

$$a_{p^{r+1}} p^{-(r+1)s} - a_p a_{p^r} p^{-(r+1)s} + p^{k-1} a_{p^{r-1}} p^{-(r+1)s} = (a_{p^{r+1}} - a_p a_{p^r} + p^{k-1} a_{p^{r-1}}) p^{-(r+1)s} = 0,$$

since $a_{p^{r+1}} = a_p a_{p^r} - p^{k-1} a_{p^{r-1}}$. So

$$L(s, f) = \prod_p \sum_{k=0}^{\infty} a_{p^k} p^{-ks} = \prod_p \frac{1}{1 - a_p p^{-s} + p^{k-1} p^{-2s}}.$$

□

Lecture 21 is a problem class.

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2 Modular forms of higher level

2.1 Modular forms

2.1.1 Congruence subgroups

$\mathrm{GL}_2(\mathbb{Q})_+$ acts on \mathbb{H} by fractional linear transformations.

Definition 2.1.1. $\Gamma(N) \subseteq \mathrm{SL}_2(\mathbb{Z})$ is the kernel of $\mathrm{SL}_2(\mathbb{Z}) \rightarrow \mathrm{SL}_2(\mathbb{Z}/N\mathbb{Z})$ for $N \in \mathbb{Z}_{>0}$. Alternatively,

$$\Gamma(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z}) \mid a \equiv d \equiv 1 \pmod{N}, b \equiv c \equiv 0 \pmod{N} \right\}.$$

Note. $\Gamma(N) \subseteq \mathrm{SL}_2(\mathbb{Z})$ has finite index.

Definition 2.1.2. $\Gamma \subseteq \mathrm{GL}_2(\mathbb{Q})_+$ is a **congruence subgroup** if Γ contains $\Gamma(N)$ with finite index for some $N \in \mathbb{Z}_{>0}$.

Example. $\mathrm{SL}_2(\mathbb{Z})$ and $\Gamma(N)$ are congruence subgroups. Let

$$\Gamma_0(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z}) \mid c \equiv 0 \pmod{N} \right\},$$

and

$$\Gamma_1(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z}) \mid a \equiv d \equiv 1 \pmod{N}, c \equiv 0 \pmod{N} \right\},$$

so $\Gamma_1(N)$ is the preimage of

$$\begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \subseteq \mathrm{SL}_2(\mathbb{Z}/N\mathbb{Z})$$

in $\mathrm{SL}_2(\mathbb{Z})$. Then $\Gamma_0(N)$ and $\Gamma_1(N)$ are congruence subgroups such that

$$\Gamma(N) \subseteq \Gamma_1(N) \subseteq \Gamma_0(N) \subseteq \mathrm{SL}_2(\mathbb{Z}).$$

Proposition 2.1.3. Let $\alpha \in \mathrm{GL}_2(\mathbb{Q})_+$, and let Γ be a congruence subgroup. Then $\alpha\Gamma\alpha^{-1}$ is also a congruence subgroup.

Proof. Need that there exists M with $\Gamma(M) \subseteq \alpha\Gamma\alpha^{-1}$ with finite index. There exists N such that $\Gamma(N) \subseteq \Gamma$. Note that $\Gamma(N) = \mathrm{SL}_2(\mathbb{Q}) \cap (\mathrm{I}_2 + N \mathrm{Mat}_2 \mathbb{Z})$. Consider

$$\alpha\Gamma(N)\alpha^{-1} = \mathrm{SL}_2(\mathbb{Q}) \cap (\mathrm{I}_2 + N\alpha \mathrm{Mat}_2 \mathbb{Z}\alpha^{-1}).$$

Choose $n \in \mathbb{Z}$ such that $n\alpha$ and $n\alpha^{-1}$ have entries in \mathbb{Z} . Then $n^2\alpha^{-1} \mathrm{Mat}_2 \mathbb{Z}\alpha \subseteq \mathrm{Mat}_2 \mathbb{Z}$, so $n^2 \mathrm{Mat}_2 \mathbb{Z} \subseteq \alpha \mathrm{Mat}_2 \mathbb{Z}\alpha^{-1}$, so $Nn^2 \mathrm{Mat}_2 \mathbb{Z} \subseteq N\alpha \mathrm{Mat}_2 \mathbb{Z}\alpha^{-1}$, so

$$\Gamma(n^2N) = \mathrm{SL}_2(\mathbb{Q}) \cap (\mathrm{I}_2 + Nn^2 \mathrm{Mat}_2 \mathbb{Z}) \subseteq \mathrm{SL}_2(\mathbb{Q}) \cap (\mathrm{I}_2 + N\alpha \mathrm{Mat}_2 \mathbb{Z}\alpha^{-1}) = \alpha\Gamma(N)\alpha^{-1}.$$

Similarly, show

$$\alpha\Gamma(n^4N)\alpha^{-1} \subseteq \Gamma(n^2N) \subseteq \alpha\Gamma(N)\alpha^{-1}.$$

Since $\Gamma(n^4N)$ has finite index in $\Gamma(N)$, $\Gamma(n^2N)$ has finite index in $\alpha\Gamma(N)\alpha^{-1}$. \square

Note. If $T = \mathrm{lcm}(M, N)$ then $\Gamma(T) \subseteq \Gamma(M) \cap \Gamma(N)$, so the intersection of two congruence subgroups is a congruence subgroup.

Example. Let

$$\alpha = \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}.$$

Then

$$\alpha^{-1} \mathrm{SL}_2(\mathbb{Z}) \alpha = \left\{ \begin{pmatrix} a & p^{-1}b \\ pc & d \end{pmatrix} \mid \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z}) \right\},$$

and

$$\alpha^{-1} \mathrm{SL}_2(\mathbb{Z}) \alpha \cap \mathrm{SL}_2(\mathbb{Z}) = \left\{ \begin{pmatrix} a & b \\ pc & d \end{pmatrix} \mid ad - pbc = 1 \right\} = \Gamma_0(p).$$

2.1.2 Modular forms

Recall that for $f : \mathbb{H} \rightarrow \mathbb{C}$ and $\alpha \in \mathrm{GL}_2(\mathbb{Q})_+$, we defined $f|_{k,\alpha}$ by

$$f|_{k,\alpha}(z) = \det \alpha^{k-1} f(\alpha z) (cz + d)^{-k}.$$

Suppose we have a $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Q})$ and $f : \mathbb{H} \rightarrow \mathbb{C}$ such that $f|_{k,\gamma} = f$ for all $\gamma \in \Gamma$. Then if $g = f|_{k,\alpha}$, then $g|_{k,\gamma} = g$ for all $\gamma \in \alpha^{-1}\Gamma\alpha$, since

$$(f|_{k,\alpha})|_{k,\gamma} = f|_{k,\gamma\alpha} = (f|_{k,\gamma})|_{k,\alpha} = f|_{k,\alpha}.$$

Definition 2.1.4. Fix $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Q})$ a congruence subgroup. A function $f : \mathbb{H} \rightarrow \mathbb{C}$ is a **weakly holomorphic or meromorphic modular form of weight k and level Γ** if

- $f|_{k,\gamma} = f$ for all $\gamma \in \Gamma$, and
- f is holomorphic or meromorphic on \mathbb{H} .

A question is what condition should we impose at ∞ to get a good theory?

Example. Let $k \geq 4$ and $N \in \mathbb{Z}$, and let

$$E_k^{0,1}(z) = \sum_{(m,n) \in S^{0,1}} \frac{1}{(mz + n)^k}, \quad S^{0,1} = \{(m,n) \in \mathbb{Z}^2 \setminus \{0\} \mid m \equiv 1 \pmod{N}, n \equiv 0 \pmod{N}\}.$$

Claim that $E_k(\gamma z) = E_k(z)$ for $\gamma \in \Gamma(N)$. Let $\gamma \in \Gamma(N)$. Then

$$\begin{aligned} E_k^{0,1}(\gamma z) &= \sum_{(m,n) \in S^{0,1}} \frac{1}{\left(m \left(\frac{az+b}{cz+d}\right) + n\right)^k} \\ &= (cz + d)^k \sum_{(m,n) \in S^{0,1}} \frac{1}{(m(az + b) + n(cz + d))^k} \\ &= (cz + d)^k \sum_{(m,n) \in S^{0,1}} \frac{1}{((ma + nc)z + (mb + nd))^k}, \end{aligned}$$

so $m \equiv a \equiv d \equiv 1 \pmod{N}$ and $n \equiv b \equiv c \equiv 0 \pmod{N}$, so $ma + nc \equiv 1 \pmod{N}$ and $mb + nd \equiv 0 \pmod{N}$. So $(ma + nc, mb + nd) \in S^{0,1}$. Moreover, the map

$$\begin{array}{ccc} S^{0,1} & \longleftrightarrow & S^{0,1} \\ (m,n) & \longmapsto & (ma + nc, mb + nd) \\ (m'a' + n'c', m'b' + n'd') & \longleftarrow & (m', n') \end{array}, \quad \gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, \quad \gamma^{-1} = \begin{pmatrix} a' & b' \\ c' & d' \end{pmatrix}$$

is a bijection. So

$$E_k^{0,1}(\gamma z) = E_k^{0,1}(z) (cz + d)^k.$$

Every congruence subgroup is conjugate to a subgroup of $\mathrm{SL}_2(\mathbb{Z})$, but

$$\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z})$$

need not be in Γ . On the other hand, if $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Z})$, then Γ has finite index in $\mathrm{SL}_2(\mathbb{Z})$, so there exists a minimal $n_\Gamma > 0$ such that

$$\begin{pmatrix} 1 & n_\Gamma \\ 0 & 1 \end{pmatrix} \in \Gamma.$$

Then if f is weakly modular of weight k and level Γ , know $f(z + n_\Gamma) = f(z)$ for all z , so f is a function of q^{1/n_Γ} . Let $g(q^{1/n_\Gamma})$ be a function on $\mathbb{D} \setminus \{0\}$ such that $f(z) = g(e^{2\pi iz/n_\Gamma})$. Then if g is meromorphic on \mathbb{D} , can express g as a Laurent series in q^{1/n_Γ} . We say f is **meromorphic at ∞** , and the series for q is its **q -expansion**.

Example. For $\Gamma = \Gamma_0(N)$ or $\Gamma = \Gamma_1(N)$, $n_\Gamma = 1$. For $\Gamma = \Gamma(N)$, $n_\Gamma = N$.

2.1.3 A fundamental domain

A question is for $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Z})$, can we write down a fundamental domain for Γ ? For $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Z})$, write $\mathrm{SL}_2(\mathbb{Z}) = \bigsqcup_{\gamma_i \in \mathrm{SL}_2(\mathbb{Z})} \pm \gamma_i \cdot \Gamma$. Set

$$\mathcal{D}_\Gamma = \bigcup_{\gamma_i \in \mathrm{SL}_2(\mathbb{Z})} \gamma_i^{-1} \cdot \mathcal{D}.$$

Theorem 2.1.5.

1. For all $z \in \mathbb{H}$, there exists $\gamma \in \Gamma$ such that $\gamma z \in \mathcal{D}_\Gamma$.
2. The subset $\{z \in \mathcal{D}_\Gamma \mid \Gamma \cdot z \cap \mathcal{D}_\Gamma \neq \{z\}\}$ is contained in $\bigcup_{\gamma_i \in \mathrm{SL}_2(\mathbb{Z})} \gamma_i \cdot \partial \mathcal{D}$, so has measure zero.

That is, \mathcal{D}_Γ is a fundamental domain for Γ .

Proof.

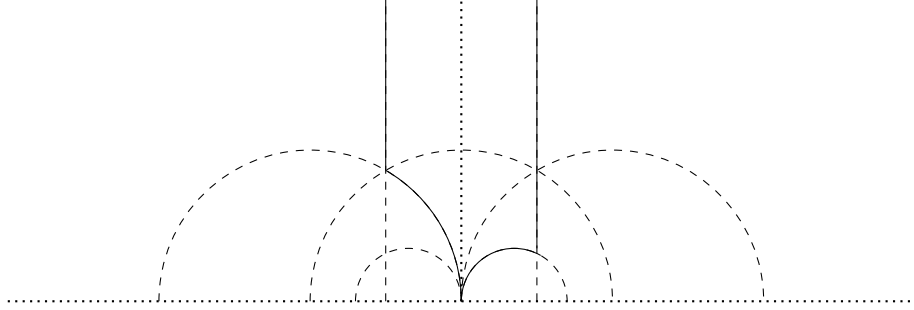
1. Fix $z \in \mathbb{H}$. There exists $\gamma \in \mathrm{SL}_2(\mathbb{Z})$ such that $\gamma z \in \mathcal{D}$. Can write γ as $\pm \gamma_i \gamma'$ for some i and $\gamma' \in \Gamma$. Then $\pm \gamma_i \gamma' z \in \mathcal{D}$, so $\gamma_i \gamma' z \in \mathcal{D}$, so $\gamma' z \in \gamma_i^{-1} \mathcal{D} \subseteq \mathcal{D}_\Gamma$.
2. Let $z \in \bigcup_{\gamma_i \in \mathrm{SL}_2(\mathbb{Z})} \gamma_i^{-1} \cdot \mathring{\mathcal{D}}$. Want $\Gamma \cdot z \cap \mathcal{D}_\Gamma = \{z\}$. Suppose $\gamma z \in \mathcal{D}_\Gamma$ for $\gamma \in \Gamma$. There exist i and j such that $z \in \gamma_i^{-1} \cdot \mathring{\mathcal{D}}$ and $\gamma z \in \gamma_j^{-1} \cdot \mathring{\mathcal{D}}$, so $\gamma_i z, \gamma_j \gamma z \in \mathring{\mathcal{D}}$. So $\gamma_i z = \gamma_j \gamma z$ so $\gamma^{-1} \gamma_j^{-1} \gamma_i z = z$. Then $\mathrm{Stab} z = \pm \mathrm{I}_2$, so $\gamma_i = \pm \gamma_j \gamma$. Since $\mathrm{SL}_2(\mathbb{Z}) = \bigsqcup_{\gamma_i \in \mathrm{SL}_2(\mathbb{Z})} \pm \gamma_i \cdot \Gamma$, this is only possible if $i = j$. Then $\gamma_i = \pm \gamma_i \gamma$, so $\gamma = \pm \mathrm{I}_2$. So $z = \gamma z$.

□

Example. $\Gamma = \Gamma_0(2)$ has index three in $\mathrm{SL}_2(\mathbb{Z})$. The coset representatives are

$$\mathrm{I}_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} : z \mapsto z, \quad \mathrm{S} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} : z \mapsto -\frac{1}{z}, \quad \mathrm{ST} = \begin{pmatrix} 0 & -1 \\ 1 & 1 \end{pmatrix} : z \mapsto -\frac{1}{z+1},$$

so



A question is for a given Γ and \mathcal{D}_Γ , what are the ways to escape to ∞ in \mathcal{D}_Γ ? Let $\Gamma \subseteq \mathrm{SL}_2(\mathbb{Z})$ be a congruence subgroup. Then

$$\mathrm{SL}_2(\mathbb{Z}) \cdot \infty = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \cdot \infty \right\} = \left\{ \frac{a}{c} \mid \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z}) \right\} = \mathbb{Q} \cup \{\infty\}.$$

Definition 2.1.6. The set of **cusps** for Γ is the set of Γ -orbits on $\mathbb{Q} \cup \{\infty\}$.

Note. If $\mathrm{SL}_2(\mathbb{Z}) = \bigsqcup_{\gamma_i \in \mathrm{SL}_2(\mathbb{Z})} \pm \gamma_i \cdot \Gamma$, then $\{\gamma_i^{-1} \cdot \infty\}$ is a set of representatives for the Γ -orbits on $\mathbb{Q} \cup \{\infty\}$.

Example. Let p be prime, and let $\Gamma = \Gamma_0(p)$. Then

$$\Gamma \cdot \infty = \left\{ \frac{a}{pc} \mid (a, pc) = 1 \right\} \cup \{\infty\}, \quad \Gamma \cdot 0 = \left\{ \frac{b}{d} \mid d \nmid p \right\}.$$

Definition 2.1.7. A weakly modular form f of weight k and level Γ is **holomorphic or meromorphic at all cusps** if for all $\gamma \in \Gamma$, $f|_{k,\gamma}$ is holomorphic or meromorphic at ∞ .

Note. Since $f|_{k,\gamma} = f$ for $\gamma \in \Gamma$, it suffices to check on a set of coset representatives for Γ in $\mathrm{SL}_2(\mathbb{Z})$.

Definition 2.1.8. A **modular form of weight k and level Γ** is a weakly modular form of weight k and level Γ that is holomorphic on \mathbb{H} and at all cusps.