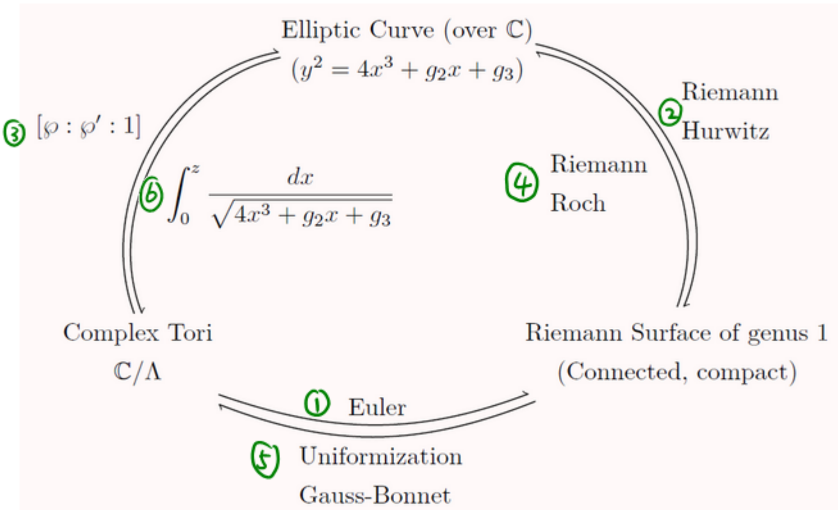
Modular form

1. origin of definition of modular form

1. EC
2. moduli space (from cplx points of view)
3. modular form

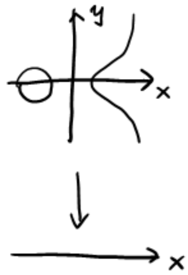
https://www.mathi.uni-heidelberg.de/~otmar/diplom/williams.pdf

1. EC



② RH formula: $f: X \to Y$ $\quad \chi = 2-2g$

$$\chi(X) = \chi(Y)\deg f - \sum_{x \in \mathrm{Ram}(f)} (e(x)-1)$$



$$\begin{array}{ccc} E & & [x:y:z] \\ \downarrow & & \downarrow \\ \mathbb{P}^1 & & [x:z] \end{array}$$

③④ $\iota: \mathbb{C}/\Lambda \longrightarrow \mathbb{P}^2$

$$z \longmapsto \begin{cases} [\wp(z) : \wp'(z) : 1] & z \neq 0 \\ [0:1:0] & z = 0 \end{cases}$$

- well-define: $/\Lambda$ + holomorphic
- equation (computation in [WWL, 命题 8.3.2])
- closed embedding [Vakil, 19.2.7, 19.2.10]

⑤ $\tilde{X}$ $\quad$ $\tilde{X}$ RS + $\Gamma \subset \mathrm{Aut}_{RS,\mathrm{tran}}(\tilde{X})$

$\downarrow$ $\quad \Rightarrow \tilde{X} \cong \mathbb{CP}^1, \mathbb{C}$ or H $\qquad \Gamma \subset \mathrm{Aut}_{RS,\mathrm{tran}}(\tilde{X}) \subset \mathrm{Isom}^+(\tilde{X})$

X $\quad \Rightarrow$ Riemannian metric with constant curverture on X

$\overset{GB}{\Rightarrow} \tilde{X} \cong \mathbb{C}$, $X = \mathbb{C}/\Lambda$

⑥ $E \xrightarrow{\cong} H^0(E, \Omega_E)^\vee / \pi_1(E,e)$

$z \longmapsto \left[\omega \longmapsto \int_{\gamma: 0 \to z} \omega\right]$

Idea:

$$\begin{array}{ccc} \tilde{E} & \xrightarrow{\sim} & H^0(E,\Omega_E)^\vee \\ \downarrow & & \downarrow \\ E & \xrightarrow{\sim} & H^0(E,\Omega_E)^\vee/\pi_1(E,e) \end{array}$$

Ex. 1. Discuss 0. Discuss addition structure and their compatabilities.
2. Some computations of $\wp, \wp'$.
3. Describe rational fct field on EC.

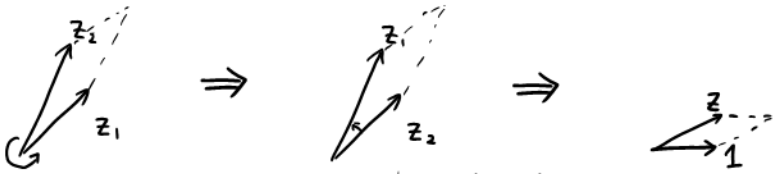
2. moduli space (from cplx points of view)

Origin of $\mathcal{H}/SL_2(\mathbb{Z})$

Lemma. $\mathbb{C}/\Lambda \cong \mathbb{C}/\Lambda' \Leftrightarrow \Lambda' = z_0 \Lambda$ $\quad \exists\, z_0 \in \mathbb{C}^\times$

Proof. [WWL, 命题 3.8.3, 练习 3.8.4]

Reduced to: Classify lattices (up to cplx scalar)



(up to cplx scalar
up to $SL_2(\mathbb{Z})$-action)

$\gamma\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} := \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$

$z \in \mathcal{H}$
(up to $SL_2(\mathbb{Z})$-action)

$\gamma z := ?$

$$
\begin{tikzcd}
\left\{(z_1,z_2)\in(\mathbb{C}\setminus\{0\})^2 \,\middle|\, \operatorname{Im}\frac{z_1}{z_2}>0\right\} \arrow[r, "\circlearrowleft\,\mathbb{C}^*", "\circlearrowleft\, SL_2(\mathbb{Z})"'] \arrow[dd] & \mathcal{H} \;\circlearrowleft SL_2(\mathbb{Z}) \arrow[d] \\
 & \mathcal{H}/SL_2(\mathbb{Z}) \\
\left\{\mathbb{C}/\Lambda \,\middle|\, \Lambda=\mathbb{Z}z_1\oplus\mathbb{Z}z_2\right\} \arrow[r, "\circlearrowleft\,\mathbb{C}^*"] & \{\mathbb{C}/\Lambda\}/\sim \arrow[u, equal] \arrow[u, bend left=80, red]
\end{tikzcd}
$$

图 2.1　构造模空间/模形式的过程

Description of $\mathcal{H}/SL_2(\mathbb{Z})$

Ex. 1. Special items of $SL_2(\mathbb{Z})$ $\quad T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$ $\quad S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

2. (difficult)  & $SL_2(\mathbb{Z}) = \langle T, S \rangle$ [Za, Prop 1] [JP, P78, Thm 1, 2]

$= \langle T, S \mid S^2, (ST)^3 \rangle$

3.  Describe glue, elliptic pts and cusp pt, volume

↑ the corresponding lattices

i: $E_{\mathbb{Z}[i]}: y^2 = x^3 + x$ $\quad \phi(x,y) = (-x, iy)$

ρ: $E_{\mathbb{Z}[\rho]}: y^2 = 4x^3 - 1$ $\quad \phi(x,y) = (\rho x, -y)$

https://math.stackexchange.com/questions/2051526/eisenstein-series-for-hexagonal-lattice?rq=1
http://www.fen.bilkent.edu.tr/~franz/publ/wald.pdf
https://math.stackexchange.com/questions/4043509/how-can-i-calculate-the-eisenstein-series-of-a-complex-lattice
https://mathematica.stackexchange.com/questions/89430/eisenstein-series-in-mathematica

1.1.2. (a) Show that $\mathrm{Im}(\gamma(\tau)) = \mathrm{Im}(\tau)/|c\tau + d|^2$ for all $\gamma = \left[\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right] \in \mathrm{SL}_2(\mathbf{Z})$.
(b) Show that $(\gamma\gamma')(\tau) = \gamma(\gamma'(\tau))$ for all $\gamma, \gamma' \in \mathrm{SL}_2(\mathbf{Z})$ and $\tau \in \mathcal{H}$.
(c) Show that $d\gamma(\tau)/d\tau = 1/(c\tau + d)^2$ for $\gamma = \left[\begin{smallmatrix} a & b \\ c & d \end{smallmatrix}\right] \in \mathrm{SL}_2(\mathbf{Z})$.

3. Modular form

Def. A holo fct $f: \mathcal{H} \longrightarrow \mathbb{C}$ is called a modular form of weight $k \in \mathbb{Z}$, level $\Gamma := SL_2(\mathbb{Z})$ if

1) $\quad f(\gamma\tau) = (c\tau + d)^k f(\tau) \qquad \forall \gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \Gamma$

e.p. $\quad f(\tau + 1) = f(\tau)$

2) Write $\quad f(\tau) = \sum_{n \in \mathbb{Z}} a_n e^{2\pi i n \tau}$, then $a_n = 0$ for $n < 0$

By cplx analysis, this condition is equivalent to $\exists C > 0$ s.t. $\{ |f(\tau)| \mid \mathrm{Im}\,\tau > C \}$ is bounded.

$M_*(\Gamma) \supseteq S_*(\Gamma)$ ← Cusp form = Spitzenform

Ex. 1. View modular form as fcts on the space of lattices

2. Eisenstein fct.

练习 2.1.1. 对于 $k \in \mathbb{Z}, k > 2$, 定义 *Eisenstein* 函数

$$G_k(\tau) := \frac{1}{2} \sum_{w \in \Lambda_\tau}{}' \frac{1}{w^k} = \frac{1}{2} \sum_{(m,n) \in \mathbb{Z}^2}{}' \frac{1}{(m\tau + n)^k}$$

其中 $\sum'$ 表示对 0 以外的点求和, 可以验证

1. 级数在 $\mathcal{H}$ 的紧子集上一致收敛, G_k 为 $\mathcal{H}$ 上的全纯函数;
2. k 为奇数时, $G_k \equiv 0$;
3. k 为偶数时, G_k 满足(2.1.1), 且有 Fourier 展开

$$G_k(\tau) = \frac{(2\pi i)^k}{(k-1)!} \left(-\frac{B_k}{2k} + \sum_{n=1}^{\infty} \sigma_{k-1}(n) q^n \right)$$

故 G_k 为权 k, 级 $SL_2(\mathbb{Z})$ 的模形式.

为方便起见, 取 $E_k := G_k/(2\zeta(k))$ 使得 Fourier 常数项化为 1. 可以证明, $M_*(SL_2(\mathbb{Z})) \cong \mathbb{C}[E_4, E_6]$, 且 E_4, E_6 代数无关.

We use $G_k(\Lambda) := \sum_{z_0 \in \Lambda}{}' \frac{1}{z_0^k}$ instead

(In [Za] $G_k(\Lambda) := \frac{1}{2} \sum_{z_0 \in \Lambda}{}' \frac{1}{z_0^k}$)

Next time

3. Δ and j

4. $M_*(SL_2(\mathbb{Z})) = \mathbb{C}[E_4, E_6]$

This will be put to Lec 3.

② mero — modular fct (of weight 0)

⑥ smooth — Automorphic form

⑧ Hilbert MF

⑦ Siegel MF

③ MF of congruence subgp

⑤ half-integral weight MF

Def. A holo fct $f: \mathcal{H} \longrightarrow \mathbb{C}$ is called a modular form of weight $k \in \mathbb{Z}$, level $\Gamma := SL_2(\mathbb{Z})$, if.

1) $f(\gamma\tau) = (c\tau+d)^k f(\tau)$ $\quad \forall \gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \Gamma$

④ almost holomorphic MF

e.p. $f(\tau+1) = f(\tau)$

2) Write $f(\tau) = \sum_{n \in \mathbb{Z}} a_n e^{2\pi i n\tau}$, then $\underbrace{a_n = 0 \text{ for } n < 0}$

① meromorphic MF

① The order I plan to talk about

(For me they become more and more difficult)