Adjoint L-value formula and Tate conjecture

Haruzo Hida
Department of Mathematics, UCLA,
Los Angeles, CA 90095-1555, U.S.A.

Talk at Columbia University, April, 2023

Abstract: For a Hecke eigenform f, we state an adjoint L-value formula relative to each quaternion algebra D over $\mathbb{Q}$ with discriminant ∂ and reduced norm N. A key to prove the formula is the theta correspondence for the quadratic $\mathbb{Q}$-space (D, N). Under the $R = \mathbb{T}$-theorem, p-part of the Bloch-Kato conjecture is known; so, the formula is an adjoint Selmer class number formula. We also describe how to relate the formula to a consequence of the Tate conjecture for quaternionic Shimura varieties.

§0. Class number formulas.

Dirichlet's class number formula in 1839:

$$\frac{\sqrt{d}\cdot L(1,\left(\frac{-d}{}\right))}{2\pi} = \sum_{\mathfrak{a}\in Cl_K} e^{-1} \quad (e = |O_K^\times|, CL_K := \text{class group})$$

for an imaginary quadratic field $K = \mathbb{Q}[\sqrt{-d}]$.

Siegel's mass formula in 1935 for a definite quaternion algebra $D_{/\mathbb{Q}}$ with an Eichler order R of level N:

$$\mathfrak{m} = \mathfrak{m}_1\frac{\zeta(2)}{\pi^2} = \sum_{\mathfrak{a}\in Cl_D} e_{\mathfrak{a}}^{-1}, \quad \mathfrak{a}\in Cl_D = D^\times\backslash D_{\mathbb{A}}^\times/\widehat{R}^\times D_\infty^\times = Sh_R$$

where Cl_D is the right ideal classes and $e_{\mathfrak{a}} = |\{\alpha\in D|\alpha\mathfrak{a}\subset\mathfrak{a}\}^\times|$ with the rational part of Siegel's mass $\mathfrak{m}_1$. If D has prime discriminant p and $N=1$, $\mathfrak{m}_1 = (p-1)/2$.

Allow now an indefinite quaternion algebra with its Shimura curve Sh_R. Consider the quadratic space (D,N) for type reduced norm N, whose even Clifford group is almost $G = G_D := D^\times \times D^\times$ by the action $v\mapsto h^{-1}vg$ for $h,g\in D^\times$.

§**1. Two formulas.** Let $\delta(Sh_R)$ be the diagonal image of Sh_R in $Sh_R \times Sh_R$. Choose well Schwartz-Bruhat functions ϕ, ϕ' on $D_{\mathbb{A}}$. Write $\theta^*(\phi)(f)$ for the theta lift of $S^{new}(\Gamma_0(\partial N))$ to G and $\theta_*(\phi)(\mathcal{F} \otimes \mathcal{G}) \in S_2(\Gamma_0(\partial N))$ ($\mathcal{F}, \mathcal{G} : Sh_R \to \mathbb{C}$) for the theta descent. Assume that $\int_{Sh_R} \mathcal{F} d\mu = \int_{Sh_R} \mathcal{G} d\mu = 0$ (cuspidality).

Theorem A: *We have* $\theta_*(\phi)(\mathcal{F} \otimes \mathcal{G}) = \sum_{n=1}^{\infty} (\mathcal{F}, \mathcal{G}|T(n))q^n$ *for* $q = \exp(2\pi i\tau)$ *with* $(\mathcal{F}, \mathcal{G}) = \int_{\delta(Sh_R)} \mathcal{F}(h)\mathcal{G}(h) d\mu_h$. *So* $\theta_*(\phi)$ *and* $\theta^*(\phi)$ *are Hecke equivariant.*

Theorem B:

$$\prod_{p|\partial} (1 - p^{-2})^{-1} \mathfrak{m}_1 \frac{L(1, Ad(\rho_f))}{2\pi^3}$$

$$= \begin{cases} \int_{\delta(Sh_R)} \theta^*(\phi')(f)(h) d\mu_h & \text{if } D_\infty \cong M_2(\mathbb{R}) \\ \sum_{\mathfrak{a} \in \delta(Sh_R)} \frac{\theta^*(\phi')(f)(\mathfrak{a})}{e_{\mathfrak{a}}} & \text{if } D_\infty \cong \mathbb{H}. \end{cases}$$

Under $R = \mathbb{T}$ theorem at a prime p, p-primary Bloch-Kato conjecture known for $Ad(\rho_f)$; so, This is an adjoint Selmer class number formula after dividing by the canonical period $\Omega_+\Omega_-$.

§2. **Theta kernel.** If D is definite, Schwartz function $\phi_\infty(\tau; v_\infty)$ is given by $\mathbf{e}(N(v_\infty)\tau)$ ($\tau \in \mathfrak{H}$: the upper half complex plane). If indefinite, we follow Shimura's choice. For a Bruhat function $\phi^{(\infty)}$ on $D_{\mathbb{A}}^{(\infty)}$, we have the theta series

$$\theta(\phi)(\tau; h_l, h_r) = \sum_{\alpha \in D} \phi(h_l^{-1}\alpha h_r)\phi_\infty(\tau; h_l^{-1}\alpha h_r) \quad \text{on } \mathfrak{H} \times G_D(\mathbb{A})$$

which can be extended to an automorphic form on $Y_\Gamma \times Sh \times Sh$ for $Sh := D^\times \backslash D_{\mathbb{A}}^\times / D_\infty^\times$ and $Y_\Gamma := \Gamma\backslash\mathfrak{H}$ for a congruence subgroup Γ. For a weight 2 cusp form $f \in S_2(\Gamma)$ and automorphic forms $\mathcal{F}, \mathcal{G} : Sh \to \mathbb{C}$, we define

$$\theta^*(\phi)(f)(h_l, h_r) = \int_{Y_\Gamma} f(\tau)\theta(\phi)(\tau; h_l, h_r) y^{-2} dx dy, \quad (h_l, h_r \in D_{\mathbb{A}}^\times)$$

$$\theta_*(\phi)(\mathcal{F} \otimes \mathcal{G})(\tau) = \int_{Sh \times Sh} \theta(\phi)(\tau; h_l, h_r)(\mathcal{F}(h_l) \cdot \mathcal{G}(h_r)) d\mu_l d\mu_r.$$

We choose the Haar measure $d\mu_?$ on $D_{\mathbb{A}}^\times$ suitably. We call $\theta^*(\phi)(f) : Sh \times Sh \to \mathbb{C}$ a theta lift and $\theta_*(\phi)(\mathcal{F} \otimes \mathcal{G}) \in M_2(\Gamma)$ a theta descent.

§3. Two good choices of Schwartz-Bruhat functions.

Case A: At N, we identify $R/NR = \left\{\begin{pmatrix} a & b \\ 0 & d \end{pmatrix} \in M_2(\mathbb{Z}/N\mathbb{Z})\right\}$ (Eichler order). Let ϕ_R be the characteristic function of

$$\left\{x \in \widehat{R} | x \bmod NR = \begin{pmatrix} a & b \\ 0 & d \end{pmatrix},\ d \in (\mathbb{Z}/N\mathbb{Z})^\times\right\}.$$

Then the first choice is

$$\phi(v) = \phi_R(v^{(\infty)})\phi_\infty(\tau; v)$$

as a Schwartz-Bruhat function on $D_\mathbb{A}$. In this case, $\Gamma = \Gamma_0(\partial N)$.

Case B: Let ϕ_L be the characteristic function of $\widehat{L}$. Choose $0 < c \in \mathbb{Z}$ and $L := \widehat{\mathbb{Z}} \oplus \widehat{R}_0$ for $R_0 = \{v \in R | \mathrm{Tr}(v) = 0\}$, and put $\phi'_{R_0} = (1 - c^3)^{-1}(\phi_{R_0} - \phi_{cR_0})$. Then we define, writing $v = z \oplus w$ with $z \in Z_\mathbb{A}$ and $w \in D_{0,\mathbb{A}}$

$$\phi'(v) = \phi_\mathbb{Z}(z^{(\infty)})\phi'_{R_0}(w^{(\infty)})\phi_\infty(\tau; v).$$

We have $\Gamma = \Gamma_0(4c^2\partial N)$.

§**4. Higher weight k and indefinite case.** For a higher weight k or an indefinite case, we need to replace the Schwartz function ϕ_∞ by a standard Schwartz function of Siegel–Shimura by multiplying a vector valued spherical function for (D, N) and then in the indefinite case, we modify $\theta(\varphi)$ (for $\varphi = \phi, \phi'$) and $\mathcal{F}$ and $\mathcal{G}$ into vector valued differential forms by the Eichler–Shimura map. Then $\mathcal{F}$ and $\mathcal{G}$ are closed harmonic 1-forms with values in a locally constant sheaf $\mathcal{L}_{n/A}$ whose fiber is the symmetric n-th tensor representation over an appropriate ring A for $n = k - 2$. We replace $(\mathcal{F}, \mathcal{G})$ by the cup product $(\mathcal{F}, \mathcal{G})_n := \int_{\delta(Sh_R)} \mathcal{F} \cup \mathcal{G}$ of $H^*(Sh_R, \mathcal{L}_{n/\mathbb{C}}) \times H^*(Sh_R, \mathcal{L}_{n,\mathbb{C}}) \to H^{2*}(Sh_R, \mathbb{C}) = \mathbb{C}$ in Theorem A ($* = 0, 1$ definite or indefinite).

In Theorem B, we pull back the class $\theta(\phi')^*(f)$ on $Sh_R \times Sh_R$ to $\delta(Sh_R)$ and integrate over $\delta(Sh_R)$. Then Theorem B is valid in general.

§**5. Canonical periods.** If D is indefinite, Sh_R is a Shimura curve. Let A be a DVR at a prime $\mathfrak{p}$ such that $\mathbb{Z}[\lambda] = \mathbb{Z}[\lambda(T(n))|n \in \mathbb{Z}] \subset A \subset \mathbb{Q}[\lambda]$ for the Hecke field $\mathbb{Q}[\lambda]$ of f(i.e., $f|T(n) = \lambda(T(n))f$). Define $\mathcal{F}_\pm$ by $H_\lambda := H^1(Sh_R, \mathcal{L}_{n/A})[\lambda, \pm] = A[\mathcal{F}_\pm]$, where $\pm$ indicate the $\pm$-eigenspace of complex conjugation on Sh_R. Put $H := H^1(Sh_R, \mathcal{L}_{n/A})[\pm]$ and $S := H^0(Sh_{R/A}, \omega^k_{/A})$ for the weight k Hodge bundle ω^k.

Also define $\mathcal{F}$ by $S[\lambda] = A\mathcal{F}$ $(\mathcal{F} \in S_k(\widehat{R}^\times))$. By Hodge decomposition, $H \otimes_A \mathbb{C} = S \oplus \overline{S}$. Then we project $\mathcal{F}$ to a unique element $\omega^\pm(\mathcal{F})$ of the $\pm$-eigenspace $H^1(Sh_R, \mathcal{L}_{n/\mathbb{C}})[\lambda, \pm]$ of complex conjugation and define the period $\Omega^D_\pm \in \mathbb{C}^\times$ as $\omega^\pm(\mathcal{F}) = \Omega^D_\pm[\mathcal{F}_\pm]$. The period $\Omega_\pm$ in Theorem B is $\Omega_\pm^{M_2(\mathbb{Q})}$. We just put $\Omega^D_\pm = 1$ if D is definite.

Tate conjecture predicts $\Omega^D_\pm/\Omega_\pm \in \mathbb{Q}[\lambda]^\times$ if D is indefinite.

The conjecture is known for $k = 2$ by Faltings and Prasanna for $k \geq 2$ to good extent. We hope to give a far easier proof valid also for Hilbert modular forms.

§**6. Relation to Tate conjecture.** Assume that D is indefinite. Let E be one of $H^1(Sh_R, \mathcal{L}_{n/\mathbb{Q}[\lambda]})[\pm]$. Decompose $E \otimes_A \mathbb{Q} = E_\lambda \oplus E_\lambda^\perp$ into λ-eigenspace E_λ and its Hecke stable complement, and write $\widetilde{H}_\lambda$ for the projection of H to E_λ. Define $c_D := (\mathcal{F}_+, \mathcal{F}_-)_n$ which is called cohomological D-congruence number, and $\widetilde{H}_\lambda / H_\lambda \cong A/c_D A$. We know, in $\mathbb{C}/A^\times$, under the $R = \mathbb{T}$-theorem at a prime p, forgetting about a π-power

$$(*) \quad (\mathcal{F}_+, \mathcal{F}_-)_n = c_D \overset{R=\mathbb{T}}{=} c_{M_2(\mathbb{Q})} \overset{\text{H,1981}}{=} \frac{L(1, Ad(\rho_f))}{\Omega_+ \Omega_-} \ \text{(up to } A^\times).$$

By Theorem A, for $u_\pm^D \in \mathbb{C}^\times$, $\theta_D^*(f) = u_+^D \mathcal{F}_+ \otimes u_-^D \mathcal{F}_-$. Thus

$$L(1, Ad(\rho_f)) \overset{\text{Theorem B}}{\doteq} \int_{\delta(Sh_R)} \theta_D^*(\phi')(f)$$

$$= u_+^D u_-^D (\mathcal{F}_+, \mathcal{F}_-)_n \overset{(*)}{\doteq} u_+^D u_-^D \frac{L(1, Ad(\rho_f))}{\Omega_+ \Omega_-}.$$

Thus $u_+^D u_-^D / \Omega_+ \Omega_- \in A^\times$. Thus if $u_+^D u_-^D = \Omega_+^D \Omega_-^D$ (i.e. $u_\pm^D \mathcal{F}_\pm = \omega^\pm(\mathcal{F}) \Leftrightarrow \theta_D^*(\phi') = \omega^+(\mathcal{F}) \otimes \omega^-(\mathcal{F})$), the A-integral Tate conjecture in this case holds (which I hope to prove in future).

§**7. Proof of Theorem A.** Let $h_k(\partial N; A)$ be the subalgebra of $\mathrm{End}_{\mathbb{C}}(S_k(\Gamma_0(\partial N)))$ generated over A by Hecke operators $T(n)$ and $S_k(\Gamma_0(\partial N); A) = S_k(\Gamma_0(\partial N)) \cap A[[q]]$. Recall

Duality theorem *The space $S := S_k(\Gamma_0(\partial N); A)$ is A-dual of $H := h_k(\partial N; A)$ such that for a linear form $\phi : h_k(\partial N; A) \to A$,* $\boxed{\sum_{n=1}^{\infty} \phi(T(n))q^n} \in S_k(\Gamma_0(\partial N); A)$. *Writing $f = \sum_{n=1}^{\infty} a(n, f)q^n \in S$, the pairing $\langle \cdot, \cdot \rangle : H \times S \to A$ is given by $\langle h, f \rangle = a(1, f|h)$.*

By Jacquet-Langlands correspondence, $H^*(Sh_R, \mathcal{L}_{n/A})$ is a module over $h_k(\partial N; A)$. Then applying the above theorem to the linear form $h_k(\partial N; A) \ni h \mapsto (\mathcal{F}, \mathcal{G}|h)_n$, we get Theorem A.

For the proof of Theorem B, we resort to an idea of Waldspurger.

§**8. An idea of Waldspurger.** Computing the period of $\theta^*(\phi')(f)$ for a quadratic space $V = W \oplus W^\perp$ over an orthogonal Shimura subvariety $S_W \times S_{W^\perp} \subset S_V$ has two steps:
(S) Split $\theta(\phi')(\tau, h, h^\perp) = \theta(\varphi)(\tau, h) \cdot \theta(\tau, \varphi^\perp)(h^\perp)$ $(h^? \in \mathrm{O}_{W^?}(\mathbb{A}))$ for a decomposition $\phi' = \varphi \otimes \varphi^\perp$ (φ and $\varphi^\perp$ Schwartz–Bruhat functions on $W_\mathbb{A}$ and $W^\perp_\mathbb{A}$);
(R) For the theta lift $(\theta^*(\phi')(f))(h) = \int_Y f(\tau)\theta(\phi')(\tau, h) d\mu$ with a modular curve Y, the period P over the Shimura subvariety $S \times S^\perp$ (S for $\mathrm{O}(W)$ and $S^\perp$ for $\mathrm{O}(W^\perp)$) is given by:

$$\int_{S\times S^\perp}\int_Y f(\tau)\theta(\phi')(\tau; h) d\mu(\tau) dh \quad (d\mu(\tau) = y^{-2} dx dy; \text{Seesaw})$$
$$= \int_Y f(\tau)\left(\int_{S^\perp}\theta(\varphi^\perp)(\tau; h^\perp) dh^\perp\right)\cdot\left(\int_S \theta(\varphi)(\tau; h_0) dh\right) d\mu.$$

Then invoke the Siegel–Weil formula to convert inner integrals into the Siegel-Weil Eisenstein series $E(\varphi)$ and $E(\varphi^\perp)$, reaching Rankin-Selberg integral

$$P = \int_Y f(\tau) E(\varphi^\perp) E(\varphi) d\mu = L\text{-value}.$$

§**9.** D **definite and** $n = 0$**.** For simplicity, we assume that D is definite and $n = 0$. Then $D = Z \oplus D_0$ for the center Z and $D_0 := \{v \in D | \mathrm{Tr}(v) = 0\}$. So $W = Z = (\mathbb{Q}, x^2)$ and $W^\perp = D_0$. Computing Siegel–Weil formula for $\varphi = \phi_{\mathbb{Z}}$, we have $E(\varphi) = \sum_{n=-\infty}^{\infty} q^{n^2}$ (Riemann's theta series). In the definite case, $E(\varphi^\perp)$ is a weight $\frac{3}{2}$ Eisenstein series times $\mathfrak{m}$.

For general $\varphi^\perp$, $E(\varphi^\perp)$ is the sum of the Eisenstein series $E_\infty(\varphi^\perp)$ of the infinity cusp and $E_0(\varphi^\perp)$ of the zero cusp. For the Rankin convolution, $\int_Y f\theta(\varphi)E_0(\varphi^\perp)d\mu_\tau$ causes a trouble. Our choice of $\varphi^\perp := \phi'_{R_0}$ introducing $0 < c \in \mathbb{Z}$ is made to have the vanishing $E_0(\phi'_{R_0}) = 0$ and the identity $E_\infty(\phi'_{R_0}) = E_\infty(\phi_{R_0})$. The Rankin convolution $\int_Y f\theta(\varphi)E_\infty(\phi_{R_0})d\mu_\tau$ is computed in 1976 by Shimura and produces the adjoint L-value in Theorem B. All the computation can be generalized to the Hilbert modular case over a totally real field F and a quaternion algebra $D_{/F}$.