On a conjecture of Jacquet

by

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and

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For Joe Shalika, with our admiration and appreciation.

Introduction.

Let $k$ be a number field and let $\pi_i$, $i = 1, 2, 3$ be cuspidal automorphic representations of $GL_2(\mathbb{A})$ such that the product of their central characters is trivial. Jacquet then conjectured that the central value $L(\frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3)$ of the triple product $L$-function is nonzero if and only if there exists a quaternion algebra $B$ over $k$ and automorphic forms $f_i^B \in \pi_i^B$ such that the integral

\[
I(f_1^B, f_2^B, f_3^B) = \int_{Z(\mathbb{A})B^\times(k) \backslash B^\times(\mathbb{A})} f_1^B(b) f_2^B(b) f_3^B(b) \, d^\times b \neq 0,
\]

where $\pi_i^B$ is the representation of $B^\times(\mathbb{A})$ corresponding to $\pi_i$.

In a previous paper [4], we proved this conjecture in the special case where $k = \mathbb{Q}$ and the $\pi_i$'s correspond to a triple of holomorphic newforms. Our method was based on a combination of the Garrett, Piatetski-Shapiro, Rallis integral representation of the triple product $L$-function with the extended Siegel–Weil formula and the seesaw identity. The restriction to holomorphic newforms over $\mathbb{Q}$ arose from (i) the need to invoke the Ramanujan Conjecture to control the poles of some bad local factors and (ii) the use of a version of the Siegel–Weil formula for similitudes. In this note, we show that, thanks to the recent improvement on the Ramanujan bound due to Kim–Shahidi [11], together with a slight variation in the setup of (ii), our method yields Jacquet’s conjecture in general.

Since the exposition in [4] was specialized from the start to the case of interest for certain arithmetic applications, we will briefly sketch the method in general in the first few sections. We then prove the facts required about the extended Siegel–Weil formula.

Several authors have considered interpretations of the vanishing of the central value $L(\frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3)$. Here we mention only the work of Dihua Jiang, [9], who gave an intriguing relation with a period of an Eisenstein series on $G_2$.

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§1. The integral representation of the triple product L–function.

Let $G = GSp_6$ be the group of similitudes of the standard 6 dimensional symplectic vector space over $\mathbb{k}$, and let $P = MN$ be the Siegel parabolic. For $a \in GL_3$, $b \in Sym_3$ and $\nu$ a scalar, let

$$m(a) = \left( \begin{array}{c} a \\ \nu a^{-1} \end{array} \right), \quad n(b) = \left( \begin{array}{c} 1 \\ b \\ 1 \end{array} \right), \quad \text{and} \quad d(\nu) = \left( \begin{array}{c} 1 \\ \nu \end{array} \right) \in G.$$

Let $K_G = K_{G,\infty} \cdot K_{G, f}$ be the standard maximal compact subgroup of $G(\mathbb{A})$. For $s \in \mathbb{C}$, let $\lambda_s$ be the character of $P(\mathbb{A})$ defined by

$$\lambda_s(d(\nu)n(b)m(a)) = |\nu|^{-3s} |\det(a)|^{2s}.$$ 

Let $I(s) = I^G_P(\lambda_s)$ be the normalized induced representation of $G(\mathbb{A})$, consisting of all smooth $K_G$–finite functions $\Phi_s$ on $G(\mathbb{A})$ such that

$$\Phi_s(d(\nu)n(b)m(a)g, s) = |\nu|^{-3s-3} |\det(a)|^{2s+2} \Phi_s(g).$$

The Eisenstein series associated to a section $\Phi_s \in I(s)$ is defined for $\text{Re}(s) > 1$ by

$$E(g, s, \Phi_s) = \sum_{\gamma \in P(\mathbb{k}) \backslash G(\mathbb{k})} \Phi_s(\gamma g),$$

and the normalized Eisenstein series is

$$E^*(g, s, \Phi_s) = b_G(s) \cdot E(g, s, \Phi_s),$$

where $b_G(s) = \zeta_{\mathbb{k}}(2s + 2) \zeta_{\mathbb{k}}(4s + 2)$, as in [16]. Note that the central character of $E(g, s, \Phi_s)$ is trivial. These functions have meromorphic analytic continuations to the whole $s$–plane and have no poles on the unitary axis $\text{Re}(s) = 0$. In particular, the map

$$E^*(0) : I(0) \longrightarrow \mathcal{A}(G), \quad \Phi_0 \mapsto (g \mapsto E^*(g, 0, \Phi_s))$$

gives a $(g_\infty, K_{G,\infty}) \times G(\mathbb{A}_f)$–intertwining map from the induced representation $I(0)$ at $s = 0$ to the space of automorphic forms on $G$ with trivial central character.

Let

$$G = (GL_2 \times GL_2 \times GL_2)_0$$

$$= \{(g_1, g_2, g_3) \in (GL_2)^3 \mid \det(g_1) = \det(g_2) = \det(g_3)\}.$$
This group embeds diagonally in $G = GSp_6$. For automorphic forms $f_i \in \pi_i$, $i = 1, 2, 3$, let $F = f_1 \otimes f_2 \otimes f_3$ be the corresponding function on $G(\mathbb{A})$. The global zeta integral [16] is given by

\begin{equation}
Z(s, F, \Phi_s) = \int_{Z_G(\mathbb{A})G(\mathbb{A})} E^*(g, s, \Phi_s) F(g) \, dg.
\end{equation}

Suppose that the automorphic forms $f_i \in \pi_i$ have factorizable Whittaker functions $W_\psi^i = \otimes_v W_\psi^i$ and that the section $\Phi_s$ is factorizable. Let $S$ be a finite set of places of $k$, including all archimedean places, such that, for $v \notin S$,

(i) the fixed additive character $\psi$ of $\mathbb{A}/k$ has conductor $O_{k,v}$ at $v$.

(ii) $\pi_{i,v}$ is unramified, $f_i$ is fixed under $K_v = GL_2(O_{k,v})$, and $W_\psi^i(e) = 1$.

(iii) $\Phi_{s,v}$ is right invariant under $G(O_{k,v}) = K_{G,v}$ and $\Phi_{s,v}(e) = 1$.

Then

\begin{equation}
Z(s, F, \Phi_s) = L^S(s + \frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) \cdot \prod_{v \in S} Z_v(s, W_\psi^v, \Phi_{s,v}),
\end{equation}

for local zeta integrals $Z_v(s, W_\psi^v, \Phi_{s,v})$, where $W_\psi^v = W_1^v W_2^v W_3^v$. Here

\begin{equation}
Z(s, W_\psi^v, \Phi_{s,v}) = \int_{Z_G(k_v)M(k_v) \backslash G(k_v)} \Phi_{s,v}(\delta g) W_\psi^v(g) \, dg,
\end{equation}

where $\delta \in G(k)$ is a representative for the open orbit of $G$ in $P \backslash G$, cf. for example [2], and

\begin{equation}
M = \{ (\begin{pmatrix} 1 & x_1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}), (\begin{pmatrix} 1 & x_2 \\ 1 \end{pmatrix}), (\begin{pmatrix} 1 & x_3 \\ 1 \end{pmatrix}) \in G \mid x_1 + x_2 + x_3 = 0 \}.
\end{equation}

Here $L^S(s, \pi_1 \otimes \pi_2 \otimes \pi_3)$ is the triple product L-functions with the factors for $v \in S$ omitted.

§2. Local zeta integrals.

In this section, we record some consequences of recent results of Kim and Shahidi [11] on the Ramanujan estimate for the $\pi_i$’s. We begin by recalling relevant aspects of the local theory of the triple product, as recently completed by Ikeda and Ramakrishnan. In the following proposition by “local Euler factor” at a finite place $v$ of $k$ we mean a function of the form $P(q_v^{-s})^{-1}$, where $P$ is a polynomial, $P(0) = 1$, and $q_v$ is the order of the residue field; at an archimedean field we mean a finite product of Tate’s local Euler factors for $GL(1)$.

**Proposition 2.1.** Let $v$ be a place of $k$ and let $\pi_{i,v}$, $i = 1, 2, 3$, be a triple of admissible irreducible representations of $GL(2, k_v)$ that arise as local components at $v$ of cuspidal automorphic representations $\pi_i$. 
(i) There exists a local Euler factor \( L(s, \pi_1, v \otimes \pi_2, v \otimes \pi_3, v) \) such that, for any local data \((W_v^\psi, \Phi_{s,v})\), the quotient

\[ \tilde{Z}_v(s, W_v^\psi, \Phi_{s,v}) = Z_v(s, W_v^\psi, \Phi_{s,v}) \cdot L(s + \frac{1}{2}, \pi_1, v \otimes \pi_2, v \otimes \pi_3, v)^{-1} \]

is entire as a function of \( s \).

(ii) Let \( \sigma_{i,v}, i = 1, 2, 3 \), be the representations of the Weil-Deligne group of \( k_v \) associated to \( \pi_{i,v} \) by the local Langlands correspondence. Then

\[ L(s, \pi_1, v \otimes \pi_2, v \otimes \pi_3, v) = L(s, \sigma_1, v \otimes \sigma_2, v \otimes \sigma_3, v). \]

(iii) For any finite place \( v \), there is a local section \( \Phi_{s,v} \) and a Whittaker function \( W_v^\psi = W_{1,v}^\psi \cdot W_{2,v}^\psi \cdot W_{3,v}^\psi \), such that

\[ Z(s, \Phi_{s,v}, W_v^\psi) \equiv 1. \]

(iv) For any archimedean place \( v \), there exists a finite collection of Whittaker functions \( W_v^\psi \cdot \Phi_{s,v} \) and of sections \( \Phi_{s,v} \), holomorphic in a neighborhood of \( s = 0 \) such that

\[ \sum_j Z(0, \Phi_{s,v}, W_v^\psi \cdot \Phi_{s,v}) = 1. \]

Proof. For \( v \) non-archimedean, assertion (i) is proved in §3, Appendix 3, of [16]; see [7], p. 227 for a concise statement. For \( v \) real or complex, (i) and (ii) were proved in several steps by Ikeda, of which the crucial one is [8], Theorem 1.10. Assertion (ii) in general is due to Ramakrishnan, [19], Theorem 4.4.1. For the moment, the hypothesis that the \( \pi_{i,v} \) embed in global cuspidal representations seems to be necessary.

Assertions (iii) and (iv) are contained in Proposition 3.3 of [16]. □

**Proposition 2.2.** (i) For any triple \( \pi_i \) of cusp forms for \( GL_2 \) over \( k \), and for any place \( v \), the local Langlands L-factor \( L(s, \pi_1, v \otimes \pi_2, v \otimes \pi_3, v) \) is holomorphic at \( s = \frac{1}{2} \).

(ii) For any place \( v \), for any triple of Whittaker functions \( W_v^\psi \) in the Whittaker spaces of \( \pi_{i,v} \), and for any section \( \Phi_{s,v} \in I_v(s) \), holomorphic in a neighborhood of \( s = 0 \), the local zeta integral \( Z(s, W_v^\psi, P_{s,v}) \) is holomorphic in a neighborhood of \( s = 0 \).

Proof. This follows from the results of Kim and Shahidi. We sketch the simple argument, quoting the proof of Proposition 3.3.2 of [19]. Let \( \sigma_{i,v} \) correspond to
\( \pi_{i,v} \) as in the previous proposition. For the present purposes we can assume each \( \pi_i \) to be unitary. Indeed, this can be arranged by twisting \( \pi_i \) by a (unique) character of the form \( | \cdot |^a \), where \( | \cdot | \) is the idèle norm and \( a_i \in \mathbb{C} \). Since the product of the central characters of \( \pi_i \) is trivial, we have \( a_1 + a_2 + a_3 = 0 \), so the triple product \( L \)-factor is left unaffected.

To each \( \pi_{i,v} \), necessarily generic and now assumed unitary, we can assign an index \( \lambda_{i,v} \) which measures the failure of \( \pi_{i,v} \) to be tempered; we have \( \lambda_{i,v} = t \) if \( \pi_{i,v} \) is a complementary series attached to \( (\mu | \cdot |^t, \mu | \cdot |^{-t}) \) with \( t > 0 \) and \( \mu \) unitary, \( \lambda_{i,v} = 0 \) otherwise. Then, according to [19], (3.3.10),

(2.1) \( L(s, \pi_{1,v} \otimes \pi_{2,v} \otimes \pi_{3,v}) \) is holomorphic for \( \text{Re}(s) > \lambda(\pi_{1,v}) + \lambda(\pi_{2,v}) + \lambda(\pi_{3,v}) \).

Now (i) follows from (2.1) and the Kim-Shahidi estimate \( \lambda(\pi_{i,v}) < \frac{5}{34} \) for all \( i \) and all \( v \) [11], whereas (ii) follows from (i), and Proposition 2.1 (i) and (ii). \( \square \)

By (1.8), (1.9), and the holomorphy of \( E^\ast(g, s, \Phi) \) on the unitary axis, the expression

(2.2) \( L^S(s + \frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) \cdot \prod_{v \in S} Z_v(s, F, \Phi_{s,v}) \)

\[ = \int_{Z_G(\mathbb{A})G(\mathbb{k}) \backslash G(\mathbb{A})} E^\ast(g, s, \Phi_s) F(g) \, dg. \]

is holomorphic at \( s = 0 \) for all choices of data \( F \) and \( \Phi_s \). By varying the data for places in \( S \) and applying (iii) and (iv) of Proposition 2.1, it follows that the partial Euler product \( L^S(s + \frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) \) is holomorphic at \( s = 0 \). By (i) of Proposition 2.2, the Euler product \( L(s + \frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) \) over all finite places is holomorphic at \( s = 0 \), and we obtain the identity

(2.3) \( L(\frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) \cdot \prod_{v \in S} Z^\ast_v(0, W^\psi_v, \Phi_{s,v}) \)

\[ = \int_{Z_G(\mathbb{A})G(\mathbb{k}) \backslash G(\mathbb{A})} E^\ast(g, 0, \Phi_s) F(g) \, dg. \]

where

(2.4) \( Z^\ast_v(s, W^\psi_v, \Phi_{s,v}) = \begin{cases} \hat{Z}_v(s, W^\psi_v, \Phi_{s,v}) & \text{if } v \in S_f, \\ Z_v(s, W^\psi_v, \Phi_{s,v}) & \text{if } v \in S_\infty. \end{cases} \)

Corollary 2.3. \( L(\frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) = 0 \) if and only if

\[ \int_{Z_G(\mathbb{A})G(\mathbb{k}) \backslash G(\mathbb{A})} E^\ast(g, 0, \Phi_s) F(g) \, dg = 0, \]

for all choices of \( F \in \mathcal{I} = \pi_1 \otimes \pi_2 \otimes \pi_3 \) and \( \Phi_s \in I(s) \).

Of course, relation (2.3) gives a formula for \( L(\frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3) \) for a suitable choice of \( F \) and \( \Phi_s \).
§3. The Weil representation for similitudes.

The material of this section is a slight variation on that of section 5 of [3]. We consider only the case of the dual pair \((GO(V), GSp_6)\) where the space \(V\) has square discriminant.

Let \(B\) be a quaternion algebra over \(k\) (including the possibility \(B = M_2(k)\)), and let \(V = B\) be a 4 dimensional quadratic space over \(k\) where the quadratic form is given by \(Q(x) = \alpha \nu(x)\), where \(\nu\) is the reduced norm on \(B\) and \(\alpha \in k^\times\). Note that the isomorphism class of \(V\) is determined by \(B\) and the sign of \(\alpha\) at the set \(\Sigma_\infty(B)\) of real archimedean places of \(k\) at which \(B\) is division. Let \(H = GO(V)\) and let \(H_1 = O(V)\) be the kernel of the scale map \(\nu : H \to \mathbb{G}_m\). Let \(G = GSp_6\), and let \(G_1 = Sp_6\) be the kernel of the scale map \(\nu : G \to \mathbb{G}_m\). We want to extend the standard Weil representation \(\omega = \omega_\psi\) of \(H_1(\mathbb{A}) \times G_1(\mathbb{A})\) on the Schwartz space \(S(V(\mathbb{A})^3)\). First, there is a natural action of \(H(\mathbb{A})\) on \(S(V(\mathbb{A})^3)\) given by

\[
(3.1) \quad L(h)\varphi(x) = |\nu(h)|^{-3} \varphi(h^{-1}x).
\]

For \(g_1 \in G_1(\mathbb{A})\) one has

\[
(3.2) \quad L(h)\omega(g_1)L(h)^{-1} = \omega(d(\nu)g_1d(\nu)^{-1}),
\]

where \(\nu = \nu(h)\), and \(d(\nu)\) is as in section 1. Therefore, one obtains a representation of the semidirect product \(H(\mathbb{A}) \ltimes G_1(\mathbb{A})\) on \(S(V(\mathbb{A})^3)\). Let

\[
(3.3) \quad R = \{(h, g) \in H \times G \mid \nu(h) = \nu(g)\}.
\]

Then there is an isomorphism

\[
(3.4) \quad R \to H \times G_1, \quad (h, g) \mapsto (h, d(\nu(g))^{-1}g) = (h, g_1),
\]

(this defines a map \(g \mapsto g_1\)) and a representation of \(R(\mathbb{A})\) on \(S(V(\mathbb{A})^3)\) given by

\[
(3.5) \quad \omega(h, g)\varphi(x) = (L(h)\omega(g_1)\varphi)(x) = |\nu(h)|^{-3}(\omega(g_1)\varphi)(h^{-1}x).
\]

The theta distribution \(\Theta\) on \(S(V(\mathbb{A})^3)\) is invariant under \(R(k)\), since, for \((h, g) \in R(k)\),

\[
\Theta(\omega(h, g)\varphi) = \sum_{x \in V(k)^3} |\nu(h)|^{-3}(\omega(g_1)\varphi)(h^{-1}x)
\]

\[
(3.6) \quad = \sum_{x \in V(k)^3} (\omega(g_1)\varphi)(x)
\]

\[
= \Theta(\omega(g_1)\varphi) = \Theta(\varphi),
\]
since \( g_1 \in G_1(k) \). The theta kernel, defined for \((h,g) \in R(A)\) by
\[
(3.7) \quad \theta(h,g; \varphi) = \sum_{x \in V(k)^3} \omega(h,g)\varphi(x),
\]
is thus left \( R(k) \) invariant.

**Remark 3.1.** Aside from a shift in notation, the convention here is essentially the same as in section 5 of [3] and section 3 of [4], except that we take pairs \((h,g)\) here versus \((g,h)\) there. Compare (3.5) above with (5.1.5) of [3]. It turns out that this seemingly slight shift in convention will crucial for the extension of the Siegel–Weil formula to similitudes, as we will see below.

Note that the set of archimedean places \( \Sigma_\infty(B) \) introduced above is the set of all real archimedean places of \( k \) at which \( V \) is definite (positive or negative). Then,
\[
(3.8) \quad G(A)^+ := \{ g \in G(A) \mid \nu(g) \in \nu(H(A)) \}
= \{ g \in G(A) \mid \nu(g)_v > 0, \forall v \in \Sigma_\infty(V) \}.
\]
For \( g \in G(A)^+ \), and \( \varphi \in S(V(A)^3) \), and for \( V \) anisotropic over \( k \), i.e., for \( B \neq M_2(k) \), the theta integral is defined by
\[
(3.9) \quad I(g, \varphi) = \int_{H_1(k) \backslash H_1(A)} \theta(h_1h, g; \varphi) \, dh_1,
\]
where \( h \in H(A) \) with \( \nu(h) = \nu(g) \). It does not depend on the choice of \( h \).

In the case \( B = M_2(k) \), the theta integral must be defined by regularization. If \( k \) has a real place, the procedure outlined on p.621 of [4], [15], using a certain differential operator to kill support, can be applied. An analogous procedure using an element of the Bernstein center can be applied at a nonarchimedean place, [23]. We omit the details.

**Lemma 3.2.** (i) (Eichler’s norm Theorem) If \( \alpha \in \nu(H(A)) \cap k^\times \), then there exists an element \( h \in H(k) \) with \( \nu(h) = \alpha \).

(ii) The theta integral is left invariant under \( G(A)^+ \cap G(k) \).

(iii) The theta integral has trivial central character, i.e., for \( z \in Z_G(A) \subset G(A)^+ \),
\[
I(zg, \varphi) = I(g, \varphi).
\]

**Proof.** (i) is a standard characterization of \( \nu(H(k)) \) is the present case. To check (ii), given \( \gamma \in G(A)^+ \cap G(k) \), choose \( \gamma' \in H(k) \) with \( \nu(\gamma') = \nu(\gamma) \). Then
\[
I(\gamma g, \varphi) = \int_{H_1(k) \backslash H_1(A)} \theta(h_1\gamma'h, \gamma g; \varphi) \, dh_1
= \int_{H_1(k) \backslash H_1(A)} \theta(\gamma'h_1h, \gamma g; \varphi) \, dh_1
= I(g, \varphi),
\]

(3.10)
via the left invariance of the theta kernel under \((\gamma', \gamma) \in R(\mathbb{k})\). Here, in the next to last step, we have conjugated the domain of integration \(H_1(\mathbb{k}) \backslash H_1(\mathbb{A})\) by the element \(\gamma' \in H(\mathbb{k})\).

Finally, the proof of (iii) is just like that of Lemma 5.1.9 (ii) in [3]. □

Since \(G(\mathbb{A}) = G(\mathbb{k})G(\mathbb{A})^+\), it follows that \(I(g, \varphi)\) has a unique extension to a left \(G(\mathbb{k})\)-invariant function on \(G(\mathbb{A})\). Moreover, for any \(g_0 \in G(\mathbb{A})^+\), we have

\[
I(gg_0, \varphi) = I(g, \omega(h_0, g_0)\varphi),
\]

where \(h_0 \in H(\mathbb{A})\) with \(\nu(h_0) = \nu(g_0)\). In particular, if \(h_1 \in H_1(\mathbb{A})\), then

\[
I(g, \omega(h_1)\varphi) = I(g, \varphi).
\]

§4. The Siegel–Weil formula for \((GO(V), GSp_6)\).

First we recall the Siegel–Weil formula for \((O(V), Sp_6)\). The results of [15] on the regularized Siegel–Weil formula were formulated over a totally real number field, since, at a number of points, we needed facts about degenerate principal series, intertwining operators, etc. which had not been checked for complex places. The proof in the case of the central value of the Siegel–Eisenstein series is simpler than the general case, and the additional facts needed at complex places are easy to check. In the rest of this section, we will state the results for an arbitrary number field \(\mathbb{k}\). A sketch of the proof of Theorem 4.1 below for such a field \(\mathbb{k}\) will be given in the Appendix below.

Let \(I_1(s) = I_{P_1}^G(\lambda_s)\) be the global induced representation of \(G_1(\mathbb{A}) = Sp_6(\mathbb{A})\) induced from the restriction of the character \(\lambda_s\) of \(P(\mathbb{A})\) to \(P_1(\mathbb{A}) = P(\mathbb{A}) \cap G_1(\mathbb{A})\).

For a global quadratic space \(V\) of dimension 4 over \(\mathbb{k}\) associated to a quaternion algebra \(B\), as in the previous section, there is a \((g_1,\infty, K_{G_1,\infty}) \times G_1(\mathbb{A})_f\)-equivariant map

\[
S(V(\mathbb{A})^3) \longrightarrow I_1(0), \quad \varphi \mapsto [\varphi],
\]

where

\[
[\varphi](g_1) = (\omega(g_1)\varphi)(0).
\]

The image, \(\Pi_1(V)\), is an irreducible summand of the unitarizable induced representation \(I_1(0)\). By the results of Rallis [17], Kudla–Rallis [14], [13], and the appendix,

\[
\Pi_1(V) \simeq S(V(\mathbb{A})^3)_{O(V)(\mathbb{A})},
\]
the space of $H_1(\mathbb{A}) = O(V)(\mathbb{A})$–coinvariants. One then has a decomposition

\[ I_1(0) = \left( \bigoplus_V \Pi_1(V) \right) \oplus \left( \bigoplus_V \Pi_1(V) \right), \]

into irreducible representations of $G_1(\mathbb{A})$, as $V$ runs over the isomorphism classes of such spaces and as $V$ runs over the incoherent collections, obtained by switching one local component of a $\Pi_1(V)$, cf. [12].

The Siegel–Weil formula of [4], asserts the following in the present case.

**Theorem 4.1.** (i) The $(g_1,\infty,K \subset G_1,\infty) \times G_1(\mathbb{A})$–intertwining map

\[ E_1(0) : I_1(0) \longrightarrow \mathcal{A}(G_1), \quad \Phi_0 \mapsto (g_1 \mapsto E(g_1,0,\Phi_s)) \]

has kernel $\bigoplus_V \Pi_1(V)$.

(ii) For a section $\Phi_s \in I_1(s)$ with $\Phi_0 = [\varphi]$ for some $\varphi \in S(V(\mathbb{A})^3)$,

\[ (SW) \quad E(g_1,0,\Phi_s) = 2I(g_1,\varphi), \]

for the theta integral as defined in §3.

As explained in the previous section, the theta integral can be extended to an automorphic form on $G(\mathbb{A})$. We will see presently that it coincides with an Eisenstein series on $G(\mathbb{A})$.

Restriction of functions from $G(\mathbb{A})$ to $G_1(\mathbb{A})$ yields an isomorphism $I(s) \xrightarrow{\sim} I_1(s)$, which is intertwining for the right action of $G_1(\mathbb{A})$. Here $I(s)$ is the induced representation of $G(\mathbb{A})$ defined in section 1. The inverse map is given by $\Phi_s \mapsto \Phi_s^\sim$ where

\[ (4.5) \quad \Phi_s^\sim(g) = |\nu(g)|^{-3s-3}\Phi_s(g_1), \]

for $g_1 = d(\nu(g))^{-1}g$, as above. The decomposition (4.4) into $G_1(\mathbb{A})$–irreducibles yields a decomposition

\[ (4.6) \quad I(0) = \left( \bigoplus_B \Pi(B) \right) \oplus \left( \bigoplus_B \Pi(B) \right), \]

into irreducible representations of $G(\mathbb{A})$, where, for a global quaternion algebra $B$ over $\mathbb{k}$,

\[ (4.7) \quad \Pi(B) = \bigoplus_V \Pi(V) \]

where $V$ runs over the non-isomorphic spaces associated to $B$ (i.e., different multiples of the norm form) and $\Pi(V)$ denotes the image of $\Pi_1(V)$ under the inverse of
the restriction isomorphism. Note that there are $2^{|\Sigma_{\infty}(B)|}$ such $V$'s. In effect, at a real archimedean place $v$, the local induced representation $I_1(0)_v$ has a decomposition into irreducible $(g_{1,v}, K_{G,1,v})$–modules

\[(4.8) \quad I(0)_v = \Pi(4,0)_v \oplus \Pi(2,2)_v \oplus \Pi(0,4)_v\]

according to signatures. The space $\Pi(2,2)_v$ is actually stable under $(g_v, K_{G,v})$, as is the sum $\Pi(4,0)_v \oplus \Pi(0,4)_v$, and

\[(4.9) \quad \Pi(B)_v = \begin{cases} 
\Pi(2,2)_v & \text{if } B_v \simeq M_2(\mathbb{R}). \\
\Pi(4,0)_v \oplus \Pi(0,4)_v & \text{if } B_v \text{ is division.}
\end{cases} \]

The summands $\Pi(B)$ are defined similarly.

**Theorem 4.2.** (i) The $(g_\infty, K_{G,\infty}) \times G(\mathbb{A}_f)$–intertwining map

\[E(0) : I(0) \longrightarrow \mathcal{A}(G), \quad \Phi_s \mapsto (g \mapsto E(g,0,\Phi_s))\]

has kernel $\oplus_B \Pi(B)$.

(ii) For a section $\Phi_s \in I(s)$ with $\Phi_0 \in \Pi(V)$ so that $\Phi_0 = [\varphi]^\sim$ for some $\varphi \in S(V(\mathbb{A})^3)$,

\[(GSW) \quad E(g,0,\Phi_s) = 2I(g,\varphi),\]

for the theta integral as defined in §3.

**Proof.** For $g_0 \in G(\mathbb{A}_f)$, we have

\[(4.10) \quad E(gg_0,s,\Phi_s) = E(g,s,r_s(g_0)\Phi_s),\]

where $r_s$ denotes the action in the induced representation $I(s)$ by right translation. Taking the value at $s = 0$, we obtain

\[(4.11) \quad E(gg_0,0,\Phi_s) = E(g,0,r_s(g_0)\Phi_s).\]

Note that this value depends only on $\Phi_0$ and $r_0(g_0)\Phi_0$.

**Lemma 4.3.** For $\varphi \in S(V(\mathbb{A})^3)$, let $[\varphi] \in I_1(0)$ be defined by (4.2) and let $[\varphi]^\sim$ be the corresponding function in $I(0)$ under the inverse of the restriction isomorphism.

(i) For $g \in G(\mathbb{A})^+$,

\[ [\varphi]^\sim(g) = (\omega(h,g)\varphi)(0), \]

where $h \in GO(V)(\mathbb{A})$ with $\nu(h) = \nu(g)$.

(ii) For $g_0 \in G(\mathbb{A}_f)$,

\[ r_0(g_0)[\varphi]^\sim = [\omega(h_0,g_0)\varphi]^\sim, \]
where \( h_0 \in \GO(V)(\mathbb{A}_f) \) with \( \nu(h_0) = \nu(g_0) \).

**Proof.** For (i), we have

\[
[\varphi] \sim (g) = [\varphi] \sim (d(\nu)g_1)
= |\nu|^{-3}[\varphi](g_1)
= |\nu|^{-3}(\omega(g_1)\varphi)(0)
= (L(h)\omega(g_1)\varphi)(0)
= (\omega(h, g)\varphi)(0).
\]

(4.12)

For (ii),

\[
(r_0(g_0)[\varphi] \sim )(g) = |\nu|^{-3}[\varphi] \sim (g_1 g_0)
= |\nu|^{-3}(\omega(h_0, g_1 g_0)\varphi)(0)
= |\nu|^{-3}(\omega(g_1)\omega(h_0, g_0)\varphi)(0)
= |\nu|^{-3}[\omega(h_0, g_0)\varphi](g_1)
= [\omega(h_0, g_0)\varphi] \sim (g).
\]

(4.13)

\( \square \)

Thus, if \( \Phi_0 = [\varphi] \sim \), then \( r_0(g_0)\Phi_0 = [\omega(h_0, g_0)\varphi] \sim \). Since \( G(\mathbb{A}) = G(k)Z_G(\mathbb{A})G_1(\mathbb{A})G(\mathbb{A}_f) \), we have, by (4.11),

\[
E(g, 0, \Phi_s) = E(\gamma g_1 g_0, 0, \Phi_s)
= E(g_1, 0, r_s(g_0)\Phi_s),
\]

(4.14)

the value at \( g_1 \) of the Siegel–Eisenstein series attached to \( \omega(h_0, g_0)\varphi \in S(V(\mathbb{A})^2) \).

On the other hand, by (3.11),

\[
I(g, \varphi) = I(\gamma g_1 g_0, \varphi)
= I(g_1, \omega(h_0, g_0)\varphi).
\]

(4.15)

Thus (GSW) follows from (SW). \( \square \) \( \square \)
§5. Proof of Jacquet’s conjecture.

Applying the Siegel–Weil formula for similitudes to the basic identity (2.3), we obtain

\[
L\left(\frac{1}{2}, \pi_1 \otimes \pi_2 \otimes \pi_3\right) \cdot Z^*(F, \Phi) \tag{5.1}
\]

\[
= \int_{\mathcal{Z}_{G(A)G(A)}^G(A)} E^*(g, 0, \Phi_\nu) F(g) \, dg
\]

\[
= 2\zeta_k(2) \sum_V \int_{\mathcal{Z}_{G(A)G(A)}^G(A)} I(g, \varphi^V) F(g) \, dg.
\]

where

\[
Z^*(F, \Phi) = \prod_{v \in S} Z^*_v(0, W_\psi, \Phi_s,v),
\]

and where \(\varphi^V \in S(V(A)^3)\), and, in fact, only a finite set of \(V\)’s occurs in the sum. More precisely, in the decomposition (4.6),

\[
\Phi_0 = \sum_V [\varphi^V] \sim + \text{terms in the } \Pi(B)’s \in I(0),
\]

where the quaternion algebras \(B\) associated to \(V\)’s are split outside the set \(S\), due to condition (iii) in the definition of \(S\) in section 1.

Now consider the integral in the last line of (5.1) for a fixed \(\varphi = \varphi^V\). To apply the seesaw identity, we set

\[
H = GO(V)
\]

(5.4)

\[
\mathcal{H} = \{(h_1, h_2, h_3) \in H^3 \mid \nu(h_1) = \nu(h_2) = \nu(h_3)\},
\]

\[
\mathcal{R} = \{(h, g) \in \mathcal{H} \times \mathcal{G} \mid \nu(h) = \nu(g)\}
\]

\[
R_0 = \{(h, g) \in \mathcal{H} \times \mathcal{G} \mid \nu(h) = \nu(g)\},
\]

and hence have the seesaw pair:

\[
I(\cdot, \varphi; F) \quad (\text{GO}(V)^3)_0 = \mathcal{H} \quad \mathcal{G} = \text{GSp}_6 \quad I(\cdot, \varphi)
\]

(5.5)

\[
\mathcal{I} \quad \text{GO}(V) = \mathcal{H} \quad \text{G} = (\text{GL}_2^3)_0 \quad F
\]

There are representations of both \(R(A)\) and \(R(A)\) on \(S(V(A)^3)\), and the restriction of these representations to the common subgroup \(R_0(A)\) coincide.

For \(F\) a cuspidal automorphic form on \(G(A)\) and for \(h \in H(A)\), let

\[
I(h, \varphi; F) = \int_{G_1(A)} \theta(h, g_1 \varphi) F(g_1 g) \, dg_1,
\]

where \(g \in G(A)\) with \(\nu(g) = \nu(h)\).
Lemma 5.1. (Seesaw identity)

\[
\int_{Z_G(\mathbb{A})G(k) \backslash G(\mathbb{A})} I(g, \varphi) F(g) \, dg = \int_{Z_H(\mathbb{A})H(k) \backslash H(\mathbb{A})} I(h, \varphi; F) \, dh.
\]

Proof. Note that \( Z_G(\mathbb{A})G(k) \backslash G(\mathbb{A}) \simeq Z_G(\mathbb{A})G(k) \backslash G(\mathbb{A})^+ \), and that

\[
Z_G(\mathbb{A})G(k)^+ \backslash G(\mathbb{A})^+ \simeq Z_H(\mathbb{A})H(k) \backslash H(\mathbb{A}) \simeq \mathbb{A}^{x,2} k^{x,+} \backslash \mathbb{A}^{x,+} =: C,
\]

is compact, where \( \mathbb{A}^{x,+} = \nu(H(\mathbb{A})) \) and \( k^{x,+} = \nu(H(k)) \). Fixing a Haar measure \( dc \) giving \( C \) volume 1, we have

\[
\int_{Z_G(\mathbb{A})G(k) \backslash G(\mathbb{A})} I(g, \varphi) F(g) \, dg
\]

(5.8)

\[
= \int_C \int_{G_1(\mathbb{A}) \backslash G_1(\mathbb{A})} \int_{H_1(\mathbb{A}) \backslash H_1(\mathbb{A})} \theta(h_1 h(c), g_1 g(c); \varphi) F(g_1 g(c)) \, dh_1 \, dg_1 \, dc
\]

\[
= \int_{Z_H(\mathbb{A})H(k) \backslash H(\mathbb{A})} I(h, \varphi; F) \, dh,
\]

generalizing the proof of Proposition 7.1.4 of [3]. □

To apply the seesaw identity to the restriction to \( G(\mathbb{A}) \) of a function \( F \in \Pi = \pi_1 \otimes \pi_2 \otimes \pi_3 \), we recall the description, from sections 7 and 8 of [4], of the corresponding space of functions \( \Theta(\Pi) \) on \( H(\mathbb{A}) \) spanned by the \( I(h, \varphi; F)'s \) for \( F \in \Pi \) and \( \varphi \in S(V(\mathbb{A})^3) \). Note that one obtains the same space by fixing a nonzero \( F \) and only varying \( \varphi \) [5].

The action of \( B^x \times B^x \) on \( V = B \), \( \rho(b_1, b_2)x = b_1 x b_2^{-1} \) determines an extension

(5.9) \[ 1 \rightarrow \mathbb{G}_m \rightarrow (B^x \times B^x) \times \langle t \rangle \rightarrow H = GO(V) \rightarrow 1 \]

where the involution \( t \) acts on \( V \) by \( \rho(t)(x) = x^t \) and on \( B^x \times B^x \) by \( (b_1, b_2) \mapsto (b_2', b_1')^{-1} \). Write

(5.10) \[ \bar{H} = (B^x \times B^x) \times \langle t \rangle \quad \text{and} \quad \bar{H}^0 = B^x \times B^x, \]

and let \( \tilde{H} \) and \( \tilde{H}^0 \) be the analogous groups for \( H = (GO(V)^3)_0 \). Thus, we have the diagram

\[
\begin{array}{c}
\tilde{\Theta}(\Pi) \quad \quad \quad \Theta(\Pi) \\
\tilde{H}^0 & \leftrightarrow & \tilde{H} & \rightarrow & H \\
\text{↑} & \quad & \text{↑} & \quad & \text{↑} \\
\bar{H}^0 & \leftrightarrow & \bar{H} & \rightarrow & H
\end{array}
\]
For an irreducible cuspidal automorphic representation $\pi$ of $GL_2(\mathbb{A})$, let $\pi^B$ be the associated automorphic representation of $B^\times(\mathbb{A})$ under the Jacquet-Langlands correspondence. We take $\pi^B$ to be zero if $\pi$ does not correspond to a representation of $B^\times(\mathbb{A})$. Similarly, let $\Pi^B = \pi^B(\mathcal{I}) \otimes \pi^B \otimes \pi^B$ be the corresponding representation of $B^\times(\mathbb{A})^3$, or zero if some factor does not exist. Note that the central character of $\Pi^B$ is trivial, and so, $(\Pi^B)^\vee \simeq \Pi^B$, where $(\Pi^B)^\vee$ is the contragradient of $\Pi^B$. Thus we can view the space of of functions $\Pi^B$ on $B^\times(\mathbb{A})^3$ as the automorphic realization of both $\Pi^B$ and its contragredient.

The following result is proved in [4], sections 7 and 8, based on the work of Shimizu and Prasad.

**Proposition 5.2.** (i) $\Theta(\Pi)$ is either zero or a cuspidal automorphic representation of $\tilde{H}(\mathbb{A})$ and is nonzero if and only if $\Pi^B$ is nonzero.
(ii) As spaces of functions on $\tilde{H}^0(\mathbb{A})$,

$$
\tilde{\Theta}(\Pi)|_{\tilde{H}^0(\mathbb{A})} = \left( \Pi^B \otimes (\Pi^B)^\vee \right)|_{\tilde{H}^0(\mathbb{A})}.
$$

For fixed $F \in \Pi$ and $\varphi \in S(V(\mathbb{A})^3)$, we let $\tilde{I}(\cdot, \varphi; F)$ denote the pullback of $I(\cdot, \varphi; F)$ to $\tilde{H}(\mathbb{A})$, and, via (ii) of Proposition 5.2, we write the restriction of this function to $\tilde{H}^0(\mathbb{A})$ as

$$
\tilde{I}((\mathbf{b}_1, \mathbf{b}_2), \varphi; F) = \sum_{\mathbf{r}} I^{1,\mathbf{r}}(\mathbf{b}_1, \varphi; F) I^{2,\mathbf{r}}(\mathbf{b}_2, \varphi; F)
$$

for functions $I^{1,\mathbf{r}}(\cdot, \varphi; F) \in \Pi^B$ and $\mathbf{b}_i \in B^\times(\mathbb{A})^3$. The seesaw then gives

$$
\int_{Z_{\tilde{G}(\mathbb{A})}G(\mathbb{k}) \backslash G(\mathbb{A})} I(g, \varphi) F(g) \, dg = \int_{Z_{\tilde{H}(\mathbb{A})}H(\mathbb{k}) \backslash H(\mathbb{A})} I(h, \varphi; F) \, dh
$$

$$
= \int_{Z_{\tilde{H}^0(\mathbb{A})}H(\mathbb{k}) \backslash \tilde{H}(\mathbb{A})} \tilde{I}(h, \varphi; F) \, dh
$$

$$
= \int_{Z_{\tilde{H}^0(\mathbb{A})}\tilde{H}^0(\mathbb{k}) \backslash \tilde{H}^0(\mathbb{A})} \tilde{I}(h, \varphi; F) \, dh
$$

$$
= \sum_{\mathbf{r}} \int_{\mathcal{A} \times B^\times(\mathbb{k}) \backslash B^\times(\mathbb{A})} I^{1,\mathbf{r}}(\mathbf{b}_1, \varphi; F) \, db_1 \cdot \int_{\mathcal{A} \times B^\times(\mathbb{k}) \backslash B^\times(\mathbb{A})} I^{2,\mathbf{r}}(\mathbf{b}_2, \varphi; F) \, db_2
$$

The fact that the integral over $Z_{\tilde{H}^0(\mathbb{A})}\tilde{H}(\mathbb{k}) \backslash \tilde{H}(\mathbb{A})$ in the third line can be replaced by the integral over $Z_{\tilde{H}^0(\mathbb{A})}\tilde{H}^0(\mathbb{k}) \backslash \tilde{H}^0(\mathbb{A})$ is (7.3.2), p.632 of [4]; its proof in section
Finally, we observe that the integrals in this last expression are finite linear combinations of the quantities \(I(f_B^1, f_B^2, f_B^3)\) of (0.1) and that, by (ii) of Proposition 5.2, every such quantity can be obtained as an integral \(\int_{\mathbb{A}^\times B^\times (k) \setminus B^\times (\mathbb{A})} I^{1,\tau}(b, \varphi; F) \, db_1\) for some \(\varphi, F\) and \(r\).

This finishes the proof of Jacquet’s conjecture.

**Remark 5.3.** In fact, by Prasad’s uniqueness theorem, if the root number

\[
\epsilon(1/2, \pi_1 \otimes \pi_2 \otimes \pi_3) = 1,
\]

then there is a unique \(B\) for which \(\Pi^B \neq 0\) and for which the space of global invariant trilinear forms on \(\Pi^B\) has dimension 1. The *automorphic* trilinear form is given by integration over \(\mathbb{A}^\times B^\times (k) \setminus B^\times (\mathbb{A})\) if and only if \(L(1/2, \pi_1 \otimes \pi_2 \otimes \pi_3) \neq 0\). Choose \(f_i^B \in \pi_i^B, i = 1, 2, 3\), such that

\[
I(f_1^B, f_2^B, f_3^B) \neq 0.
\]

For any nonzero \(F \in \Pi\), we can choose \(\varphi \in S(V(\mathbb{A}))^3\) such that

\[
\tilde{I}((b, b'), \varphi; F) = f_1^B(b_1) f_2^B(b_2) f_3^B(b_3) f_1^B(b'_1) f_2^B(b'_2) f_3^B(b'_3),
\]

where \(b = (b_1, b_2, b_3)\) and \(b' = (b'_1, b'_2, b'_3)\). We then obtain

\[
L(1/2, \pi_1 \otimes \pi_2 \otimes \pi_3) \cdot Z^*(F, \Phi) = 2\zeta_k(2)^2 I(f_1^B, f_2^B, f_3^B)^2.
\]

where, \(\Phi\) is determined by \(\varphi\), and \(Z^*(F, \Phi) \neq 0\). Of course, this identity is only useful when one has sufficient information about the function \(\varphi\) and the product of local zeta integrals \(Z^*(F, \Phi)\). This was a main concern in [4].

On the other hand, when the root number \(\epsilon(1/2, \pi_1 \otimes \pi_2 \otimes \pi_3) = -1\), then there is no \(\Pi^B\) which supports an invariant trilinear form, and the central value of the triple product L-function vanishes due to the sign in the functional equation.

**Appendix: The Siegel–Weil formula for general \(k\).**

In this appendix, we will sketch the proof of Theorem 4.1 for an arbitrary number field \(\mathbb{k}\), indicating the additional facts which are needed when \(\mathbb{k}\) has complex places.

First, suppose that \(v\) is a complex place of \(\mathbb{k}\) and consider the local degenerate principal series representation \(I_{1,v}(0)\) of \(G_{1,v} = \text{Sp}_3(\mathbb{C})\) and the Weil representation of \(G_{1,v}\) on \(S(V_v^3)\), where \(V_v \simeq M_2(\mathbb{C})\) with \(Q(x) = \text{det}(x)\).
Lemma A.1. (i) $I_{1,v}(0)$ is an irreducible unitarizable representation of $G_{1,v}$.
(ii) (Coinvariants) The map $S(V_v^3) \to I_{1,v}(0)$, $\varphi \mapsto [\varphi]$, analogous to (4.1) induces an isomorphism
\[ S(V_v^3)_{H_{1,v}} \cong I_{1,v}(0). \]

Here $H_1 = O(V)$.

Remark: Statement (i) is in Sahi’s paper, [21], Theorem 3A. The proof of (ii) was explained to us by Chen-bo Zhu [25], and is based on the method of [24].

In the case $B = M_2(k)$, the theta integral must be defined by regularization, – cf. the remarks before Lemma 3.2 above. can be applied. Alternatively, Siegel–Weil formula for certain We write

\[ I_{reg}(g_1, \varphi) = \begin{cases} 
I(g_1, \varphi) & \text{if } V \text{ is anisotropic,} \\
B_{-1}(g_1, \varphi) & \text{if } V \text{ is isotropic,}
\end{cases} \]

where $B_{-1}$ is as in (5.5.24) of [15], except that we normalize the auxiliary Eisenstein series $E(h, s)$ to have residue 1 at $s'_0$. The key facts which we need are the following.

Lemma A.2. (i) The map $I_{reg} : S(V(A)^3) \to A(G_1)$ factors through the space of coinvariants $S(V(A)^3)_{H_1(A)} = \Pi(V)$.
(ii) For all $\beta \in \text{Sym}_3(k)$, $\beta \in \text{Sym}_3(k)$
\[ I_{reg, \beta}(g_1, \varphi) = \frac{1}{2} \int_{H_1(A)} \omega(g_1)\varphi(h^{-1}x) \, dh, \]

where $x \in V(k)^3$ with $Q(x) = \beta$.

The second statement here is Corollary 6.11 of [15]; it asserts that the nonsingular Fourier coefficients behave as though no regularization were involved.

Next we have the analogue of Lemma 4.2, p.111 of [18]; the main point of the proof is the local uniqueness, and the ‘submersive set’ argument for the archimedean places carries over for a complex place.

Lemma A.3. For $\beta \in \text{Sym}_3(k)$ with $\det(\beta) \neq 0$, let $T_\beta$ be the space of distributions $T \in S(V(A)^3)'$ such that
(i) $T$ is $H(A)$–invariant.
(ii) For all $b \in \text{Sym}_3(A_f)$,
\[ T(\omega(n(b)\varphi) = \psi_\beta(b) T(\varphi), \]

³He also directed us to [21]. We wish to thank him for his help on these points.
where $\psi_\beta(b) = \psi(\text{tr}(\beta b))$.

(iii) For an archimedean place $v$ of $k$ and for all $X \in n = \text{Lie}(N)$,

\[ T(\omega(X)\varphi) = d\psi_\beta(X) \cdot T(\varphi). \]

Then $T_\beta$ has dimension at most 1 and is spanned by the orbital integral

\[ T(\varphi) = \int_{H(A)} \varphi(h^{-1} x) \, dh, \]

where $x \in V(k)^3$ with $Q(x) = \beta$. In particular, $T_\beta = 0$ if and only if there is no such $x$.

**Sketch of the Proof of Theorem 4.1.** First consider a global space $V$ associated to a quaternion algebra $B$. We have two intertwining maps

(A.2) \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \ quad
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