Local Langlands Correspondence for GL_n

As modifying files in the sciebo folder is prohibited, the corrected version of my portion (with the typo rectified) will be available in the Github directories:

Talk1:
https://github.com/ramified/personal_handwritten_collection/raw/main/weeklyupdate/2023.04.23_(non-split)_reductive_group.pdf
Talk2(this one):
https://github.com/ramified/personal_handwritten_collection/raw/main/Langlands/GL_case.pdf

F: local field NA local field + $\mathbb{R}$ & $\mathbb{C}$ case

$\Gamma_F := \mathrm{Gal}(F^{sep}/F)$
$W_F :=$ Weil group of F NA case: $W_F = \Gamma_F \times_{\hat{\mathbb{Z}}} \mathbb{Z}$
$\mathbb{C}$ case: $W_{\mathbb{C}} = \mathbb{C}^\times$
$\mathbb{R}$ case: $W_{\mathbb{R}} := \mathbb{C}^\times \sqcup j\mathbb{C}^\times \subseteq \mathbb{H}^\times$

Rep = sm rep
Irr = irr sm rep
Φ = adm irr sm rep
WDrep = Weil-Deligne rep

Let us first state the GL_n case for a NA local field F.

Thm (LLC for $GL_n(F)$, Harris-Taylor, Henniart, Scholze)
We have a natural bijection

$$\mathrm{Irr}_{\mathbb{C}}(GL_n(F)) \longleftrightarrow \mathrm{WDrep}_{\substack{n\text{-dim} \\ \text{Frob s.s}}}(W_F)$$

$$\| $$

$$\left\{ \begin{array}{ll} \rho: W_F \longrightarrow GL_n(\mathbb{C}) & \rho(\mathrm{Frob}) \text{ s.s.} \\ + \; N \in \mathrm{End}(\mathbb{C}^n) & \\ + \text{ compatability} & \end{array} \right\}$$

$n=1$

$$\chi: F^\times \longrightarrow \mathbb{C}^\times \quad \longleftrightarrow \quad \chi: W_F \twoheadrightarrow W_F^{ab} \cong F^\times \xrightarrow{\chi} \mathbb{C}^\times$$

$n=2$.

1) $\chi \circ \det \quad \longleftrightarrow \quad \left(\begin{pmatrix} \chi & \\ & \chi \cdot |\cdot|_F \end{pmatrix}, 0 \right)$

2) $n\text{-}\mathrm{Ind}_B^{GL_2}(\chi_1, \chi_2) \quad \longleftrightarrow \quad \left(\begin{pmatrix} \chi_1 & \\ & \chi_2 \end{pmatrix}, 0 \right)$

3) $\mathrm{St} \otimes (\chi \circ \det) \quad \longleftrightarrow \quad \left(\begin{pmatrix} \chi & \\ & \chi \cdot |\cdot|_F \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \right)$

4) $c\text{-}\mathrm{Ind}_{KZ}^{GL_2} \rho \quad \longleftrightarrow$ don't know how to describe

Let us try to work out $n=1$ case. In that case,

$$\begin{aligned} RHS &= \{\rho : W_F \longrightarrow \mathbb{C}^\times\} \\ &= \{\rho : W_F^{ab} \longrightarrow \mathbb{C}^\times\} \\ &\underset{\text{Artin}}{=\!=} \{\rho : F^\times \longrightarrow \mathbb{C}^\times\} = LHS \end{aligned}$$

Rem. The key argument is the Artin map

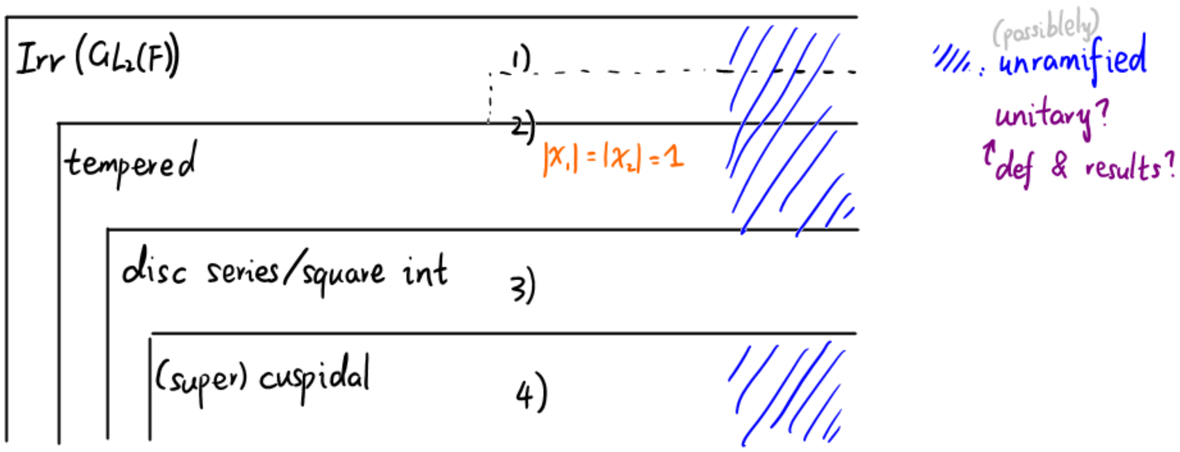
$$W_F^{ab} \cong F^\times$$

For $n=2$ case, we still have nice descriptions on both side. However, it would already take the content of a whole book for us to comprehend the details of this case.

Thm (Langlands classification for $\mathrm{Irr}_{\mathbb{C}}(GL_2(F))$)

We have a classification of $\mathrm{Irr}_{\mathbb{C}}(GL_2(F))$. $\chi : K^\times \to \mathbb{C}$

1) 1-dim $\quad \chi \circ \det$
2) principal series $\quad n\text{-}\mathrm{Ind}_B^{GL_2}(\chi_1, \chi_2) \quad \chi_1\chi_2^{-1} \neq \|\cdot\|^{\pm 1}$
3) a twist of St by χ $\quad St \otimes (\chi \circ \det)$
4) supercuspidal rep $\quad c\text{-}\mathrm{Ind}_{\mathcal{K}Z}^{GL_2} \rho \quad$ for some $\rho \in \mathrm{Irr}_{\mathbb{C}}(\mathcal{K}Z)$



For the Archimedean case, we also want to construct such a correspondence. In this case, we have a relatively explicit description on both sides, since the structure of the Weyl gp is easier. Also, we don't need to worry about cuspidal reps here.

For avoiding technical conditions. we only state the LLC for $GL_n(F)$.

$F = \mathbb{R}$ or $\mathbb{C}$.

Thm (LLC for $GL_n(F)$)

We have a 1-to-1 correspondence

$$\begin{array}{ccc} \Phi(GL_n(F))/\sim & \longleftrightarrow & \left\{ \begin{array}{l} \rho : W_F \longrightarrow GL_n(\mathbb{C}) \\ \text{semisimple as reps} \end{array} \right\} \\ \downarrow \cong & & \\ \{\text{Irr adm } (\mathfrak{gl}_n, K)\text{-modules}\} & & \end{array}$$

where

$K := O(n)$ or $U(n)$

$\sim$: up to infinitesimally equivalence

i.e. induce the same $(\mathfrak{g}, K)$-modules

For letting $n=1$ case to be true, we have to ask at least

$$W_F^{ab} \cong F^\times$$

Also, W_K should be related to Γ_F.

Def (Weil gp for $F = \mathbb{R}, \mathbb{C}$)

$$W_{\mathbb{C}} := \mathbb{C}^\times$$
$$W_{\mathbb{R}} := \mathbb{C}^\times \sqcup j\mathbb{C}^\times \subset \mathbb{H}^\times$$

Ex.

$$1 \longrightarrow \mathbb{C}^\times \longrightarrow W_{\mathbb{R}} \longrightarrow \Gamma_{\mathbb{R}} \longrightarrow 1$$

$j^2 = -1 \qquad jzj^{-1} = \bar{z}$

$\Rightarrow \frac{\bar{z}}{z} = jzj^{-1}z^{-1} \in [W_{\mathbb{R}}, W_{\mathbb{R}}]$

$\Rightarrow [W_{\mathbb{R}}, W_{\mathbb{R}}] = S^1$

$\Rightarrow W_{\mathbb{R}}^{ab} \cong (\mathbb{C}^\times \sqcup j\mathbb{C}^\times)/S^1 \cong \mathbb{R}_{>0} \sqcup j\mathbb{R}_{>0} \cong \mathbb{R}^\times$

By this iso ($W_F^{ab} \cong F^\times$), we have shown the LLC for $n=1$ case abstractly.
To understand more, we must discuss this case in more detail.

$GL_n(F)$	$\mathbb{R}$	$\mathbb{C}$
$n=1$	$\mathbb{C} \times \{\pm 1\}$ $i\mathbb{R} \times \{\pm 1\}$	$\mathbb{C} \times \mathbb{Z}$ $i\mathbb{R} \times \mathbb{Z}$
$n=2$	$\cdots$ $\mathbb{C} \times \mathbb{N}_{>0}$ $i\mathbb{R} \times \mathbb{N}_{>0}$	$\cdots$ $\emptyset$
$n>2$	$\cdots$ $\emptyset$	

$\cdots$: written as direct sum of lower dim reps.
orange: unitary representations.

E.g. $n=1$, $F=\mathbb{R}$

$$\left\{ \rho : \underset{\mathbb{R}_{>0}^\times \times \{\pm 1\}}{\overset{}{\underset{\text{\rotatebox{90}{$\cong$}}}{\mathbb{R}^\times}}} \longrightarrow \mathbb{C}^\times \right\} \cong \underset{t}{\underset{\text{\rotatebox{90}{$\in$}}}{\mathbb{C}}} \times \{\pm 1\}$$

$$\begin{aligned} x &\longmapsto x^t \\ -1 &\longmapsto \pm 1 \end{aligned} \qquad \rightsquigarrow \quad \begin{cases} \rho_{triv} \otimes |\cdot|^t \\ \rho_{sign} \otimes |\cdot|^t \end{cases}$$

The characters of $W_\mathbb{R}$ are given by

$$\begin{tikzcd} W_\mathbb{R} \arrow[r] \arrow[d] & \mathbb{C}^\times \\ \mathbb{R}^\times \cong W_\mathbb{R}^{ab} \arrow[ur, dashed, "\exists !"'] & \end{tikzcd} \qquad \begin{tikzcd} z \arrow[d, mapsto] & {|z|^t} \\ {|z|} \arrow[ur, mapsto] & \end{tikzcd} \qquad \begin{tikzcd} j \arrow[d, mapsto] & \pm 1 \\ -1 \arrow[ur, mapsto] & \end{tikzcd}$$

e.p. the unitary reps are parameterized by $i\mathbb{R} \times \{\pm 1\}$.

E.g. $n=1$, $F=\mathbb{C}$

$$\left\{ \rho : \underset{\mathbb{R}_{>0} \times S^1}{\underset{\text{\rotatebox{90}{$\cong$}}}{\mathbb{C}^\times}} \longrightarrow \mathbb{C}^\times \right\} \cong \underset{(t,l)}{\underset{\text{\rotatebox{90}{$\in$}}}{\mathbb{C} \times \mathbb{Z}}}$$

$$z = re^{i\theta} \longmapsto r^t e^{il\theta} = z^{\frac{t+l}{2}} \bar{z}^{\frac{t-l}{2}}$$

$\Big\downarrow$ reparameterization

$$z \longmapsto z^\mu \bar{z}^\nu \qquad \{(\mu, \nu) \in \mathbb{C} \times \mathbb{C} \mid \mu - \nu \in \mathbb{Z}\}$$

e.p. the unitary reps are parameterized by $i\mathbb{R} \times \mathbb{Z}$.

E.g. $n=2$, $F=\mathbb{R}$

$$\left\{\rho: W_{\mathbb{R}} \longrightarrow GL_2(\mathbb{C})\right\}/\sim$$
$$\begin{array}{ccc} \mathbb{C}^\times \subset W_{\mathbb{R}} & & \\ z & \longmapsto & \begin{pmatrix} z^{\mu}\bar{z}^{\nu} & \\ & z^{\mu'}\bar{z}^{\nu'} \end{pmatrix} \end{array}$$

① : $\rho = \chi_1 \oplus \chi_2$ $\quad \dim \chi_i = 1$

$\rightsquigarrow$ subquotient of $n\text{-}\mathrm{Ind}_B^G(\chi_1, \chi_2)$

quotient, when $\mathrm{Re}\, t_1 \geq \mathrm{Re}\, t_2$

FD & principal series

finite dim reps.

② : ρ irreducible.

By linear algebra arguments, i.e. choose a good basis

$$\left\{\rho: W_{\mathbb{R}} \longrightarrow GL_2(\mathbb{C}) \text{ irr}\right\}/\sim \;\cong\; \mathbb{C} \times \mathbb{N}_{>0}$$
$$z \longmapsto \begin{pmatrix} z^{\mu}\bar{z}^{\nu} & \\ & z^{\nu}\bar{z}^{\mu} \end{pmatrix} \qquad \left(\tfrac{\mu+\nu}{2}, \mu-\nu\right)$$
$$j \longmapsto \begin{pmatrix} & (-1)^{\mu-\nu} \\ 1 & \end{pmatrix} \qquad (t, l)$$

$\rightsquigarrow$ $DS_l \otimes |\det(-)|_{\mathbb{R}}^{t}$

$\downarrow$ discrete series $\qquad$ $\downarrow$ $\chi \circ \det$

Rem. In Prof. Caraiani's course, we did the classification of irr adm $(\mathfrak{gl}_{2,\mathbb{R}}, O(2))$-modules.
We reproduce it by the LLC!

Details about linear algebras should be put in this page.

Ref here: [Knapp91, Sec 3]: https://www.math.stonybrook.edu/~aknapp/pdf-files/motives.pdf

Step 1. Analyze $\rho|_{\mathbb{C}^\times}$

$$\left.\begin{array}{r}\rho(z) \text{ is diagonalizable} \\ \mathbb{C}^\times \text{ is commutative}\end{array}\right\} \Rightarrow \rho|_{\mathbb{C}^\times} \cong \chi_1 \oplus \chi_2$$

i.e. under some basis $\{u, v\}$,

$$\rho: z \longmapsto \begin{pmatrix} z^{\mu}\bar{z}^{\nu} & \\ & z^{\mu'}\bar{z}^{\nu'} \end{pmatrix}$$

$\rho(z)\cdot u = z^{\mu}\bar{z}^{\nu} u$

$\rho(z)\cdot v = z^{\mu'}\bar{z}^{\nu'} v$

Step 2. Remove decomposable cases.

When $\mu = \mu'$, $\nu = \nu'$: (same eigenvalues)

$$\left.\begin{array}{r}\rho(j) \text{ is diagonalizable} \\ \rho(\mathbb{C}^\times) \subset Z(GL_2(\mathbb{C}))\end{array}\right\} \Rightarrow \rho \cong \chi_1 \oplus \chi_2$$

Assume $\mu \neq \mu'$ or $\nu \neq \nu'$ now.

$$\rho(z)\rho(j)u = \rho(j)\rho(\bar{z})u = z^{\nu}\bar{z}^{\mu}\rho(j)u$$

$\Rightarrow \rho(j)u$ is an eigenvector with eigenvalue $z^{\nu}\bar{z}^{\mu}$

When $\mu = \nu$, then

$\mathbb{C}u$ is irr subrep $\rightsquigarrow \rho \cong \chi_1 \oplus \chi_2$;

When $\mu \neq \nu$, then $\mu' = \nu$, $\nu' = \mu$.

under the basis $\{u, \rho(j)u\}$,

$$\rho: z \longmapsto \begin{pmatrix} z^{\mu}\bar{z}^{\nu} & \\ & z^{\nu}\bar{z}^{\mu} \end{pmatrix}$$

$$j \longmapsto \begin{pmatrix} & ? \\ 1 & ? \end{pmatrix} \overset{j^2=-1}{=\!=\!=} \begin{pmatrix} & (-1)^{\mu-\nu} \\ 1 & \end{pmatrix}$$

Step 3. By the symmetry, we can assume that $\mu - \nu > 0$.

under the basis $\{\rho(j)u, (-1)^{\mu-\nu}u\}$,

$$\rho: z \longmapsto \begin{pmatrix} z^{\nu}\bar{z}^{\mu} & \\ & z^{\mu}\bar{z}^{\nu} \end{pmatrix}$$

$$j \longmapsto \begin{pmatrix} & (-1)^{\nu-\mu} \\ 1 & \end{pmatrix}$$

$$\left.\begin{array}{r}(\det\rho)(z) = |z|^{\nu+\mu} \\ (\det\rho)(j) = (-1)^{\nu-\mu+1} \\ \rho|_{\mathbb{C}^\times} \cong \chi_{\nu,\mu} \oplus \chi_{\mu,\nu}\end{array}\right\} \Rightarrow \begin{array}{l}(\frac{\nu+\mu}{2}, |\nu-\mu|) \in \mathbb{C}\times\mathbb{N}_{>0} \text{ are determined} \\ \text{by the rep } \rho.\end{array}$$

$\square$

Rmk. By the similar linear algebra argument, one can show

$$\rho \in \mathrm{Irr}_{\mathbb{C}}(W_{\mathbb{R}}) \rightsquigarrow \dim_{\mathbb{C}} \rho = 1 \text{ or } 2$$

$$\rho \in \mathrm{Irr}_{\mathbb{C}}(W_{\mathbb{C}}) \rightsquigarrow \dim_{\mathbb{C}} \rho = 1$$

By the correspondence, we get classifications of $GL_n(F)$-reps explicitly:

[Knapp91, p400]: https://www.math.stonybrook.edu/~aknapp/pdf-files/motives.pdf

Theorem 1. For $G = GL_n(\mathbb{R})$,

(a) if the parameters $n_j^{-1} t_j$ of $(\sigma_1, \ldots, \sigma_r)$ satisfy

$n\text{-}\mathrm{Ind}_P^{GL_n}(\sigma_1, \ldots, \sigma_r)$

$$n_1^{-1} \operatorname{Re} t_1 \geq n_2^{-1} \operatorname{Re} t_2 \geq \cdots \geq n_r^{-1} \operatorname{Re} t_r, \tag{2.5}$$

then $I(\sigma_1, \ldots, \sigma_r)$ has a unique irreducible quotient $J(\sigma_1, \ldots, \sigma_r)$,

(b) the representations $J(\sigma_1, \ldots, \sigma_r)$ exhaust the irreducible admissible representations of G, up to infinitesimal equivalence,

(c) two such representations $J(\sigma_1, \ldots, \sigma_r)$ and $J(\sigma_1', \ldots, \sigma_r')$ are infinitesimally equivalent if and only if $r' = r$ and there exists a permutation $j(i)$ of $\{1, \ldots, r\}$ such that $\sigma_i' = \sigma_{j(i)}$ for $1 \leq i \leq r$.

Q: Find a reference for the statement of $GL_n(\mathbb{C})$.