DEFORMATION OF GALOIS REPRESENTATIONS

A notes for the number theory seminar at YMSC, 2022
Update on 2022-10-13 22:24

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We are given either a number field K and a finite set of primes S, or a local field F, and we are given a representation of either $G_{K,S}$ or G_F into $\mathrm{GL}_n(k)$, where k is a finite field. We want to try to understand all possible lifts of this representation to $\mathrm{GL}_n(A)$, where A is a complete noetherian local ring with residue field k.

—Fernando Q. Gouvêa (cf. [Gou01])

Main reference: [Böc13; Maz89]
Motivation and history of deformation theory: [Maz97; Gou01]
Basics of groupoids: Appendix of [Kis09]

1. Deformations of representations of profinite groups

Notations.

p	prime number
$\mathbb{F}$	finite field of char. p
$W(\mathbb{F})$	ring of Witt vectors[1] over A
G	profinite group
$V_{\mathbb{F}}$	finite $\mathbb{F}[G]$-module with continuous G-action
d	dimeinsion of $V_{\mathbb{F}}$
$\beta_{\mathbb{F}}$	a $\mathbb{F}$-basis of $V_{\mathbb{F}}$

1.1. Deformation functors.

Notations.

$\widehat{\mathfrak{Ar}}_{W(\mathbb{F})}$	category of complete Noetherian local $W(\mathbb{F})$-algebra with residue field $\mathbb{F}$
$\mathfrak{Ar}_{W(\mathbb{F})}$	full sub-category of finite local Artinian $W(\mathbb{F})$-algebras
$\mathfrak{m}_A$	maximal ideal of $A \in \widehat{\mathfrak{Ar}}_{W(\mathbb{F})}$

Remark 1.1 (???)**.** *Via the $W(\mathbb{F})$-structure, the residue field of any $A \in \widehat{\mathfrak{Ar}}_{W(\mathbb{F})}$ is canonically isomorphic to $\mathbb{F}$.*

Definition 1.2. *Let $A \in \mathfrak{Ar}_{W(\mathbb{F})}$.*

*(1) A **deformation** of $V_{\mathbb{F}}$ to A is a pair (V_A, ι_A), such that*
   (a) V_A is $A[G]$-module, finite free over A, with continuous G-action;
   (b) $\iota_A : V_A \otimes_A \mathbb{F} \xrightarrow{\cong} V_{\mathbb{F}}$ is G-equivariant.

We view $\mathbb{F}$ as an A-module via the canonical projection $A \to A/\mathfrak{m}_A = F$.

*(2) A **framed deformation** of $(V_{\mathbb{F}}, \beta_{\mathbb{F}})$ to A is a triple (V_A, ι_A, β_A), where*

[1] $W(\mathbb{F})$ is the unique (up to unique isomorphism) complete discrete valuation ring which is absolutely unramified (uniformizer= p) and has residue field $\mathbb{F}$.

(a) (V_A, ι_A) *is a deformation of* $V_{\mathbb{F}}$ *to* A;
(b) β_A *is a* A*-basis of* V_A *which reduces to* $\beta_{\mathbb{F}}$ *under* ι_A.

Set $D_{V_{\mathbb{F}}}, D^{\square}_{V_{\mathbb{F}}} : \mathfrak{Ar}_{W(\mathbb{F})} \to \mathrm{Set}$,

$$D_{V_{\mathbb{F}}}(A) = \{\textit{deformations of } V_{\mathbb{F}} \textit{ to } A\}/\cong,$$

$$D^{\square}_{V_{\mathbb{F}}}(A) = \{\textit{framed deformations of } (V_{\mathbb{F}}, \beta_{\mathbb{F}}) \textit{ to } A\}/\cong.$$

Remark 1.3.

(1) *The* ***FIXED*** *basis* $\beta_{\mathbb{F}}$ *gives the isomorphism* $V_{\mathbb{F}} \cong \mathbb{F}^d$ *as vector space. Thus we can view* $V_{\mathbb{F}}$ *as* $\bar{\rho} : G \to \mathrm{GL}(V_{\mathbb{F}}) = \mathrm{GL}_d(\mathbb{F})$: *a* d*-dimensional* $\mathbb{F}$*-representation of* G. *Then*

$$D^{\square}_{V_{\mathbb{F}}}(A) = \{\rho : G \to \mathrm{GL}_d(A) \textit{ lifting } \bar{\rho}\},$$

$$\begin{tikzcd} G \arrow[r, "\rho"] \arrow[dr, "\bar{\rho}"'] & \mathrm{GL}_d(A) \arrow[d, two heads] \\ & \mathrm{GL}_d(\mathbb{F}) \end{tikzcd}$$

Does not guarantee $\beta_A \rightsquigarrow \beta_{\mathbb{F}}$!

$$D_{V_{\mathbb{F}}}(A) = D^{\square}_{V_{\mathbb{F}}}(A)/\textit{action by conjugates of } \ker(\mathrm{GL}_d(A) \to \mathrm{GL}_d(\mathbb{F})).$$

Not always representable!

(2) *Mazur only consdier* $D_{V_{\mathbb{F}}}$, *which describes representations lifting* $V_{\mathbb{F}}$ *up to isomorphism.*
Add "base condition" $\rightsquigarrow D^{\square}_{V_{\mathbb{F}}}$.

(3) *Often consider deformation functors on* $\mathfrak{Ar}_{\mathcal{O}}$ = *category of local artinian* $\mathcal{O}$*-algebra with residue field* $\mathbb{F}$, *where* $\mathcal{O}$ *is ring of integers of a finite totally ramified extension of* $W(\mathbb{F})\left[\frac{1}{p}\right]$ $(\mathcal{O}/\pi\mathcal{O} \cong \mathbb{F})$.
For example, let K *be a p-adic field with residue field* $\mathbb{F}_q$, *ring of integers* $\mathcal{O}_K$, *then* $K/W(\mathbb{F}_q)\left[\frac{1}{p}\right]$ *is totally ramified and* $W(\mathbb{F}_q)\left[\frac{1}{p}\right]/\mathbb{Q}_p$ *is unramified.*

1.2. Representability.

1.2.1. *A finiteness condition.*

Definition 1.4 (Mazur). *A profinite group* G *has finiteness condition* Φ_p, *if* $\forall$ *open subgroup* $G' \subset G$, $\dim_{\mathbb{F}_p} \mathrm{Hom}_{\mathrm{cont}}(G', \mathbb{F}_p) < +\infty$.

Remark 1.5.

(1) *(Burnside basis theorem)* $\dim_{\mathbb{F}_p} \mathrm{Hom}_{\mathrm{cont}}(G', \mathbb{F}_p) < +\infty \Leftrightarrow$ *maximal pro-p quotient of* G' *is topologically finitely generated.*
(2) $\mathrm{Hom}_{\mathrm{cont}}(G', \mathbb{F}_p) \cong \mathrm{Hom}_{\mathrm{cont}}(G'^{,\mathrm{ab}}, \mathbb{F}_p)$.

Example 1.6 (by CFT). *The following groups have* Φ_p:

(1) *The Galois group* $\mathcal{G}_K = \mathrm{Gal}(\bar{K}/K)$, *with* K *a p-adic field.*
(2) *The galois group* $\mathcal{G}_{F,S} = \mathrm{Gal}(F_S/F)$, *where* F *is a number field,* S *is a finite set of places of* F *and* $F_S \subset \bar{F}$ *is the maximal extension of* F *unramified outside* S.

1.2.2. *Main proposition.*

prop:1587 **Proposition 1.7** (Mazur). *If* G *has* Φ_p, *then*

(1) *The functor* $D^{\square}_{V_{\mathbb{F}}}$ *is pro-representable by some* $R^{\square}_{V_{\mathbb{F}}} \in \widehat{\mathfrak{Ar}}_{W(\mathbb{F})}$, *i.e.*

$$D^{\square}_{V_{\mathbb{F}}}(A) \cong \mathrm{Hom}_{W(\mathbb{F})}\left(R^{\square}_{V_{\mathbb{F}}}, A\right),$$

universal framed deformation ring

which is functorial in $A \in \mathfrak{Ar}_{W(\mathbb{F})}$.

Maybe it's better to write $D^{\square}_{V_{\mathbb{F}}}(A) \cong \mathrm{Hom}_{\widehat{\mathfrak{Ar}}_{W(\mathbb{F})}}(R^{\square}_{V_{\mathbb{F}}}, A)$?

(2) *If* $\mathrm{End}_{\mathbb{F}[G]}(V_{\mathbb{F}}) = \mathbb{F}$, *then* $D_{V_{\mathbb{F}}}$ *is pro-representable by some* $R_{V_{\mathbb{F}}} \in \widehat{\mathfrak{Ar}}_{W(\mathbb{F})}$.

universal deformation ring

Remark 1.8. *(1) Literally, pro-representable functor = limit of representable functor. How can we realize that? [nLa22] defines pro-representable to be the filtered colimit of representables. There's a post on MSE (cf. [htt]) which discusses the difference between the two definitions. It might be ture that*

$$\mathrm{Hom}_{W(\mathbb{F})}\left(R^{\square}_{V_{\mathbb{F}}}, A\right) = \mathrm{Hom}_{\widehat{\mathfrak{Ar}}_{W(\mathbb{F})}}\left(\varprojlim_k R^{\square}_{V_{\mathbb{F}}}/\mathfrak{m}^k_{R^{\square}_{V_{\mathbb{F}}}}, A\right) \cong \varinjlim_k \mathrm{Hom}_{\mathfrak{Ar}_{W(\mathbb{F})}}\left(R^{\square}_{V_{\mathbb{F}}}/\mathfrak{m}^k_{R^{\square}_{V_{\mathbb{F}}}}, A\right),$$

for any $A \in \mathfrak{Ar}_{W(\mathbb{F})}$.

(2) (???)$R^{\square}_{V_{\mathbb{F}}}$ is unique up to unique isomorphism; the identity map in $\mathrm{Hom}\big(R^{\square}_{V_{\mathbb{F}}}, R^{\square}_{V_{\mathbb{F}}}\big)$ gives rise to a universal framed deformation over $R^{\square}_{V_{\mathbb{F}}}$.

(3) $R^{\square}_{V_{\mathbb{F}}}$ exists without Φ_p, but maybe no longer noetherian.

(4) (???)$\mathbb{F} \hookrightarrow \mathrm{End}_{\mathbb{F}[G]}(V_{\mathbb{F}}) \rightsquigarrow$ write "=" in $\mathrm{End}_{\mathbb{F}[G]}(V_{\mathbb{F}}) = \mathbb{F}$.

prop:1587

Proof of Proposition 1.7.

(1) G finite $\rightsquigarrow$ profinite.

- **(FORMAL) CONSTRUCTION:**
  Suppose G is finite. Set
  $$G = \langle g_1, \cdots, g_s | r_1(g_1, \cdots, g_s), \cdots, r_t(g_1, \cdots, g_s)\rangle$$
  a presentation. Define
  $$\mathcal{R} = W(\mathbb{F})\big[X^k_{i,j} \big| i, j = 1, \cdots, d; k = 1, \cdots, s\big]/\mathcal{I},$$
  where
  $$\mathcal{I} = \langle r_l\big(X^1, \cdots, X^s\big) - \mathrm{id}\rangle_{1\le l\le t}, X^k = \big(X^k_{i,j}\big)_{d\times d}.$$
  To make $\mathcal{R}$ complete, local, noetherian, take
  $$\mathcal{J} = \ker\big(\mathcal{R} \to \mathbb{F}, X^k \mapsto \bar{\rho}(g_k), k = 1, \cdots, s\big),$$
  and set $R^{\square}_{V_{\mathbb{F}}} = \varprojlim_n \mathcal{R}/\mathcal{J}^n$ to be the $\mathcal{J}$-adic completion of $\mathcal{R}$. Besides that, we set $\rho^{\square}_{V_{\mathbb{F}}} : G \to \mathrm{GL}_d\big(R^{\square}_{V_{\mathbb{F}}}\big), g_k \mapsto$ image of X^k in $\mathrm{GL}_d\big(R^{\square}_{V_{\mathbb{F}}}\big)$.
  VERIFICATION:
  Take $\rho \in D^{\square}_{V_{\mathbb{F}}}(A)$, where $\rho : G \to \mathrm{GL}_d(A)$. Define
  $$\mathfrak{F}_\rho \in \mathrm{Hom}_{W(\mathbb{F})}\left(R^{\square}_{V_{\mathbb{F}}}, A\right), \overline{\text{entries of } X^k} \mapsto \text{corresponding entries of } \rho(g_k), \forall k = 1, \cdots, s.$$
  Then $\mathfrak{F}_\rho$ induces $\widehat{\mathfrak{F}_\rho} : \mathrm{GL}_d\big(R^{\square}_{V_{\mathbb{F}}}\big) \to \mathrm{GL}_d(A)$. It's immediate to check that $\rho = \widehat{\mathfrak{F}_\rho} \circ \rho^{\square}_{V_{\mathbb{F}}}$ and $\widehat{\mathfrak{F}_\rho}$ is unique choice to make the diagram commute. Thus, $\mathfrak{F} : \rho \mapsto \mathfrak{F}_\rho$ gives the pro-representability when G is finite.
- When G is profinite, we have $G = \varprojlim_i G/H_i$, where $H_i \subset \ker(\bar{\rho})$ are open normal subgroups. For every i, one has a universal pair $\big(R^{\square}_i, \rho^{\square}_i\big)$ by previous construction. Passing by limits, we define
  $$\left(R^{\square}_{V_{\mathbb{F}}}, \rho^{\square}_{V_{\mathbb{F}}}\right) = \varprojlim_i \left(R^{\square}_i, \rho^{\square}_i\right), \text{with } R^{\square}_{V_{\mathbb{F}}} \in \widehat{\mathfrak{Ar}}_{W(\mathbb{F})}.$$

We will show in [Section 1.4, TBA] that $R^{\square}_{V_{\mathbb{F}}}$ is noetherian.

(2) By Schlessinger's representability criterion (cf. [Section 1.7, TBA]) or by Kisin's work (cf. [Section 2.1, TBA by Y. Chen]).

□

1.7. **Groupid over categories (abstract stuff...)**

Definition 1.9.

*(1) A **groupoid category** is a category in which all morphisms are isomorphisms.*
*(2) Call the isomorphism classes the **connected components** of the groupoid.*

Remark 1.10.

(1) Not necessarily all objects in a groupoid are isomorphic.
(2) $\mathrm{Hom}_{\mathfrak{C}}(A,A)$ forms a group for $\forall A \in \mathrm{ob}\,\mathfrak{C}$, where $\mathfrak{C}$ is a groupoid category, and the identity in $\mathrm{Hom}_{\mathfrak{C}}(A,A)$ is the identity morphism.
(3) $A \cong B \Rightarrow \mathrm{Hom}_{\mathfrak{C}}(A,A) \cong \mathrm{Hom}_{\mathfrak{C}}(B,B)$ (non-canonically)

Definition 1.11. *Let $\mathfrak{C}$ be a category. Let $\mathfrak{F}$ be another category, $\Theta : \mathfrak{F} \to \mathfrak{C}$ be a functor.*

*(1) We say $\eta \in \mathrm{ob}(\mathfrak{F})$ **lies above** $T \in \mathrm{ob}(\mathfrak{C})$, if $\Theta(\eta) = T$.*
*(2) We say $(\eta \xrightarrow{\alpha} \zeta) \in \mathrm{Mor}_{\mathfrak{F}}$ **lies above** $(T \xrightarrow{f} S) \in \mathrm{Mor}_{\mathfrak{C}}$, if $\Theta(\eta) = f$.*
(3) $(T \in \mathrm{ob}(\mathfrak{C}), \mathrm{id}_T)$ is a subcategory of $\mathfrak{C}$. Write $\mathfrak{F}(T)$ the subcategory of $\mathfrak{F}$ over (T, id_T).

Definition 1.12 (groupoid over $\mathfrak{C}$/category cofibered in groupoids over $\mathfrak{C}$)**.** *The triple $(\mathfrak{F}, \mathfrak{C}, \Theta)$ is a **groupoid over** $\mathfrak{C}$ if*

(1) for any morphisms $(\eta \xrightarrow{\alpha} \zeta)$ and $(\eta \xrightarrow{\alpha'} \zeta')$ in $\mathfrak{F}$ over the same morphism $T \to S$ in $\mathfrak{C}$, there exists unique $\zeta \xrightarrow{u} \zeta'$ in $\mathfrak{F}$ over id_S such that $u \circ \alpha = \alpha'$.
(2) For any $\eta \in \mathrm{ob}(\mathfrak{C})$ and any $T \xrightarrow{f} S$ in $\mathrm{Mor}_{\mathfrak{C}}$ with η over T, there exists morphism $\eta \xrightarrow{\alpha} \zeta$ in $\mathrm{Mor}_{\mathfrak{F}}$ over f.

Remark 1.13. *(1) $\forall T \in \mathrm{ob}(\mathfrak{C})$, the category $\mathfrak{F}(T)$ is a groupoid. It's natural to specigy a groupoid by specifying objects in $\mathfrak{F}(T)$ for any $T \in \mathrm{ob}(\mathfrak{C})$, and specifying isomorphism class of morphisms above any $T \xrightarrow{f} S$ in $\mathfrak{C}$.*
(2) Scheme and stack stuff.....

If for each $T \in \mathrm{ob}(\mathfrak{C})$, the isomorphism classes of $\mathfrak{F}(T)$ forms a set, we associate to the category $\mathfrak{F}$ over $\mathfrak{C}$ a functor $|\mathfrak{F}| : \mathfrak{C} \to \mathrm{Set}$ by sending T to the set of isomorphism classes of $\mathfrak{F}(T)$.

eg:31408 **Example 1.14.**

(1) Let $\mathfrak{C} = \mathfrak{Ar}_{W(\mathbb{F})}$. To the representation $V_{\mathbb{F}}$ of G, we define a groupoid $\mathcal{D}_{V_{\mathbb{F}}}$ over $\mathfrak{C}$:
  (a) $\forall A \in \mathfrak{Ar}_{W(\mathbb{F})}$, objects of $\mathcal{D}_{V_{\mathbb{F}}}$ over A are pairs (V_A, ι_A) in $D_{V_{\mathbb{F}}}(A)$.
  (b) A morphism $(V_A, \iota_A) \to (V_{A'}, \iota_{A'})$ over $A \to A'$ in $\mathfrak{Ar}_{W(\mathbb{F})}$ is a isomorphism class

$$\left\{\alpha : V_A \otimes_A A' \xrightarrow{\cong} V_{A'} \text{ is an isomorphism } \middle| \iota_{A'} \circ \alpha = \iota_A\right\} \Big/ (A')^*$$

(2) Let $\mathfrak{C} = \mathfrak{Ar}_{W(\mathbb{F})}$. We define the groupoid $\mathcal{D}^{\square}_{V_{\mathbb{F}}}$ on $\mathfrak{C}$ as follows:
  (a) An object over $A \in \mathfrak{Ar}_{W(\mathbb{F})}$ is a triple (V_A, ι_A, β_A), where $(V_A, \iota_A) \in \mathcal{D}_{V_{\mathbb{F}}}(A)$and β_A is an A-basis of V_A mapping under ι_A to the basis $\beta_{\mathbb{F}}$ of $V_{\mathbb{F}}$.
  (b) A morphism $(V_A, \iota_A, \beta_A) \to (V_{A'}, \iota_{A'}, \beta_{A'})$ over $A \to A'$ is an isomorphism $\alpha : V_A \otimes_A A' \xrightarrow{\cong} V_{A'}$ taking β_A to $\beta_{A'}$.

There is an obvious morphism of groupoids $\mathcal{D}^{\square}_{V_{\mathbb{F}}} \to \mathcal{D}_{V_{\mathbb{F}}}$.

Remark 1.15.

(1) The deformation functor $D_{V_{\mathbb{F}}}$ defined before is exactly $|\mathcal{D}_{V_{\mathbb{F}}}|$ above.
(2) When $V_{\mathbb{F}}$ has non-trivial automorphisms, then so do the object in $D_{V_{\mathbb{F}}}(A)$. (???) In this situation, the groipoid $\mathcal{D}_{V_{\mathbb{F}}}$ captures the geometry of the deformation theory of $V_{\mathbb{F}}$ more accurately than its functor if isomorphism classes.

Representability of a groupoid *$\Theta : \mathfrak{F} \to \mathfrak{C}$.*

Definition 1.16.

*(1) $\forall \eta \in \mathrm{ob}(\mathfrak{F})$, define the category $\widetilde{\eta}$ (**the category under** η) as the category with objects are morphisms with source η and whose morphisms from $\eta \xrightarrow{\alpha} \zeta$ to $\eta \xrightarrow{\alpha'} \zeta'$ are morphisms $\zeta \xrightarrow{u} \zeta'$ in $\mathfrak{F}$ such that $u \circ \alpha = \alpha'$.*

ζ and ζ' are not necessarily lying on the same object of $\mathfrak{C}$

*(2) Groupoid $\mathfrak{F}$ over $\mathfrak{C}$ is **representable** if there exists $\eta \in \mathfrak{F}$ such that the canonical functor $\widetilde{\eta} \to \mathfrak{F}$ is an equivalence of categories.*

(3) Similarly, we define the category $\widetilde{T}$ for every $T \in \mathfrak{C}$.

One has a commutative diagram of categories:

$$\begin{tikzcd} \widetilde{\eta} \arrow[r] \arrow[d, "\cong"'] & \mathfrak{F} \arrow[d] \\ \widetilde{\Theta(\eta)} \arrow[r] & \mathfrak{C} \end{tikzcd}$$

Lemma 1.17. *The left vertical homorphism above is an equivalence of categories.*

Proof. Abstract nonsense...... □

Remark 1.18. *If $\mathfrak{F}$ is representable by η, then the equivalence $\widetilde{\eta} \to \widetilde{\Theta(\eta)}$ imples that η, as well as $\Theta(\eta)$, are well-defined up to canonical isomorphism. One says that $\Theta(\eta)$ **represents** $\mathfrak{F}$ **over** $\mathfrak{C}$.*

Lemma 1.19 (Relation with "classical" representable functor)**.**

(1) If $\mathfrak{F}$ is representable by η, any two objects of $\mathfrak{F}(\Theta(\eta))$ are canonically isomorphic and there is an isomorphism of functors

$$\mathrm{Hom}_{\mathfrak{C}}(T, -) \xrightarrow{\cong} |\mathfrak{F}|,$$

so that T represents $|\mathfrak{F}|$ in the usual theoretic sense.

(2) If $|\mathfrak{F}|$ is representable and for any $T \in \mathrm{ob}(\mathfrak{C})$ any two objects of $\mathfrak{F}(T)$ are related by a unique isomorphism, then $\mathfrak{F}$ is representable.

Remark 1.20. *The groupoid $\mathcal{D}_{V_{\mathbb{F}}}$ in Example 1.14 is usually not representable. Extending to $\widehat{\mathfrak{Ar}}_{W(\mathbb{F})}$ is needed.*

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A crucial question: why do we need to use the language of groupoids?

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