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Théorie des groupes/*Group Theory*

Quotients of group rings arising from two-dimensional representations

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Abstract – Suppose that ρ $G \to \mathrm{Aut}_k V$ is an absolutely irreducible two-dimensional representation of a group G over a field k Let W be a vector space over k, and σ $G \to \mathrm{Aut}_k W$ a representation such that σg is annihilated by the characteristic polynomial of ρg, for each $g \in G$ Then we prove that the $k[G]$-module W is isomorphic to a direct sum of copies of V This establishes the semisimplicity of some mod p Galois representations which occur naturally in the Jacobians of Shimura curves

Quotients d'algèbres de groupes provenant de représentations linéaires de dimension 2

Résumé – *Soit* ρ . $G \to \mathrm{Aut}_k V$ *une représentation absolument irréductible, de dimension deux, d'un groupe* G *sur un corps commutatif* k *Soit* W *un espace vectoriel sur* k, *et soit* σ $G \to \mathrm{Aut}_k W$ *une représentation avec la propriété suivante pour tout élément g de* G, σg *est annulé par le polynôme caractéristique de* ρg *Alors, on demontre que* W *est isomorphe, en tant que* $k[G]$*-module, à une somme directe de copies du module* V *On en déduit la semi-simplicité de certaines représentations modulaires du groupe de Galois* $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ *qui apparaissent de façon naturelle dans les jacobiennes des courbes de Shimura.*

Version française abrégée – Notre résultat principal est le théorème suivant :

THEOREME. – *Soit* $\rho : G \to \mathrm{Aut}_k V$ *une représentation absolument irréductible, de dimension* 2, *d'un groupe* G *sur un corps commutatif* k. *Soit* W *un espace vectoriel sur* k, *et soit* $\sigma : G \to \mathrm{Aut}_k W$ *une représentation ayant la propriété suivante : pour tout élément g de* G, σg *est annulé par le polynôme caractéristique de* ρg. *Alors,* W *est isomorphe, en tant que* $k[G]$-*module, à une somme directe de copies du module* V.

Soit k un corps commutatif. Une *involution* d'une k-algèbre E est un homomorphisme de k-espaces vectoriels $* : E \to E$ tel que $x^{**} = x$ et $(xy)^* = y^* x^*$ pour $x, y \in E$.

Soit V un espace vectoriel sur k de dimension 2. Soit * l'involution « principale » de la k-algèbre $\mathrm{End}_k V$, caractérisée par l'équation $f + f^* = \mathrm{tr}\, f$ pour $f \in \mathrm{End}_k V$. (On note tr, det : $\mathrm{End}_k V \to k$ la trace et le déterminant.) On a $ff^* = \det f$, $\mathrm{tr}\, f = \mathrm{tr}\, f^*$, $\det f = \det f^*$, et $f^2 - (\mathrm{tr}\, f) f + \det f = 0$ pour tout $f \in \mathrm{End}_k V$.

La représentation ρ induit un homomorphisme de k-algèbres $k[G] \to \mathrm{End}_k V$, noté encore ρ. On écrira simplement tr, det pour les applications $\mathrm{tr} \circ \rho$, $\det \circ \rho : k[G] \to k$.

Soit J l'idéal bilatère de $k[G]$ engendré par $\{ g^2 - (\mathrm{tr}\, g) g + \det g : g \in G \}$, et soit $R = k[G]/J$. On a $J \subseteq \ker \rho$, d'où une application $R \to \mathrm{End}_k V$ que l'on appellera encore ρ. Les applications tr et det induisent des applications tr, det : $R \to k$.

PROPOSITION 1. – *Il existe une involution* * *de* R *telle que*

$$(\rho x)^* = \rho(x^*), \qquad x + x^* = \mathrm{tr}\, x, \qquad xx^* = \det x \quad \textit{pour tout } x \in R.$$

Démonstration. – Pour $g \in G$, soit $g^* = g^{-1} . \det g \in k[G]$. Les équations $(gh)^* = h^* g^*$ et $\det g^* = \det g$ montrent que * se prolonge en une involution * de $k[G]$. On a $\rho(x^*) = (\rho x)^*$ pour tout $x \in k[G]$, comme on voit par linéarité en prenant d'abord $x = g \in G$.

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De $gg^* = \det g$ et $g^2 - (\operatorname{tr} g) g + \det g \in J$, on voit que $g + g^* \equiv \operatorname{tr} g$ (mod J) pour tout $g \in G$. Ceci donne, encore par linéarité, la congruence $x + x^* \equiv \operatorname{tr} x$ (mod J) pour $x \in k[G]$. On a, en particulier, $J^* = J$, d'où une involution * sur R telle que $\rho(x^*) = (\rho x)^*$.

On vient de démontrer la formule $x + x^* = \operatorname{tr} x$, pour $x \in R$. On a, de plus, $xx^* = \det x$ pour tout $x \in R$. En effet, l'identité $(x+y)(x+y)^* = xx^* + yy^* + \operatorname{tr}(xy^*)$ dans R, et l'identité correspondante dans $\operatorname{End}_k V$, montrent que l'ensemble $\{x \in R : xx^* \in k, \text{ et } xx^* = \det x\}$ est stable sous l'addition. Comme cet ensemble contient tout k-multiple d'un élément de G, il coïncide avec R.

Ceci démontre la proposition 1.

Par un calcul évident, la proposition implique l'identité $x^2 - (\operatorname{tr} x) x + \det x = 0$ pour tout $x \in R$. On remarque également qu'un élément $x \in R$ commute à x^*, puisque $x + x^* = \operatorname{tr} x \in k$. En utilisant l'identité $xx^* = \det x$, et la multiplicativité de det, on voit maintenant que $x \in R$ est une unité de l'algèbre R si et seulement si $\det x$ est non nul; cette dernière condition est satisfaite si et seulement si ρx est une unité de $\operatorname{End}_k V$.

PROPOSITION 2. — *Si l'homomorphisme* $k[G] \to \operatorname{End}_k V$ *est surjectif, alors l'application* $R \to \operatorname{End}_k V$ *qu'il induit est un isomorphisme.*

Démonstration. — Il suffit de démontrer l'injectivité de l'application $R \to \operatorname{End}_k V$, car son image est celle de $k[G] \to \operatorname{End}_k V$.

Soit $x \in R$ tel que $\rho x = 0$. On a $x = -x^*$, puisque $\operatorname{tr} x = 0$. Pour tout $y \in R$, on en déduit $yx = -yx^*$. Comme on a également $xy^* + yx^* = \operatorname{tr}(xy^*) = 0$, on trouve $yx = xy^*$. Ceci donne, pour $y, z \in R$, les égalités $yzx = yxz^* = xy^* z^* = x(zy)^* = zyx$, qui entraînent $(yz - zy)x = 0$. L'idéal à gauche $\operatorname{Ann} x = \{r \in R : rx = 0\}$ de R contient donc l'ensemble $\{yz - zy : y, z \in R\}$. Ceci montre que $\operatorname{Ann} x$ est un idéal bilatère de R, et que son image $\rho(\operatorname{Ann} x)$ est un idéal bilatère de $\operatorname{End}_k V$ qui contient $\{ef - fe : e, f \in \operatorname{End}_k V\}$. Or, $\operatorname{End}_k V$ est un anneau non commutatif sans idéal bilatère non trivial. On a alors $\rho(\operatorname{Ann} x) = \operatorname{End}_k V$, et, en particulier, on peut trouver $w \in R$ tel que $\rho w = 1$ et $wx = 0$. Comme on l'a remarqué ci-dessus, w est forcément une unité de R, ce qui implique la nullité de x. La démonstration de la proposition est donc achevée.

On va démontrer maintenant le théorème. Par hypothèse, l'idéal J est contenu dans le noyau de l'homomorphisme $k[G] \to \operatorname{End}_k W$. L'espace vectoriel W est alors, de façon naturelle, un R-module. Comme ρ est absolument irréductible, l'application $k[G] \to \operatorname{End}_k V$ est surjective, et par la proposition 2, elle induit un isomorphisme $R \approx \operatorname{End}_k V$. Il est bien connu que tout $\operatorname{End}_k V$-module est somme directe de sous-modules isomorphes à V. On en déduit le théorème.

Le texte anglais contient une application aux courbes modulaires et donne quelques exemples complémentaires.

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1. INTRODUCTION. — In this Note we prove the following theorem.

THEOREM 1. — *Suppose that* $\rho : G \to \operatorname{Aut}_k V$ *is an absolutely irreducible two-dimensional representation of a group* G *over a field* k. *Let* W *be a vector space over* k, *and let* $\sigma : G \to \operatorname{Aut}_k W$ *be a representation such that* σg *is annihilated by the characteristic polynomial of* ρg, *for each* $g \in G$. *Then the* $k[G]$*-module* W *is isomorphic to a direct sum of copies of* V.

The theorem becomes false if the hypotheses are relaxed in various ways, for example if three-dimensional representations are considered instead of two-dimensional representations (§ 5).

Representations satisfying our annihilation condition occur naturally in the study of division points of Jacobians of modular curves (§ 3). For example, let J be the Jacobian of the Shimura curve over **Q** which is associated to a maximal order in a rational quaternion algebra whose discriminant is the product of two prime numbers. This abelian variety comes equipped with a commuting family of Hecke operators $T_n \in \mathrm{End}(J)$, indexed by the positive integers. These operators generate a subring **T** of End (J) which has finite index in End (J) and which is free of rank dim J over **Z**. To each maximal ideal $\mathfrak{m}$ of **T** we may attach (i) a canonical two-dimensional semisimple representation V of $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ over the field $\mathbf{T}/\mathfrak{m}$, and (ii) the kernel $W = J[\mathfrak{m}]$ of $\mathfrak{m}$ on $J(\bar{\mathbf{Q}})$. The Eichler-Shimura relation for J shows that the characteristic polynomial condition of the theorem is satisfied. Hence the representation W is a direct sum of copies of V whenever V is absolutely irreducible. In [5], the third author constructs a series of examples where V is absolutely irreducible and W has dimension 4. In that case, we have an isomorphism of representations $W \approx V \oplus V$.

2. PRINCIPLE OF THE PROOF. — The action of G on W may be interpreted as a homomorphism $k[G] \to \mathrm{End}_k W$. The hypothesis on W states that this homomorphism is trivial on the two-sided ideal J of $k[G]$ generated by $\{g^2 - (\mathrm{tr}\,\rho g) g + \det \rho g : g \in G\}$. Hence W is naturally a module over the ring $R = k[G]/J$.

Analogously, the action of G on V may be interpreted as a homomorphism $\lambda : R \to \mathrm{End}_k V$. Since the representation V is assumed to be absolutely irreducible, λ is surjective. We prove that λ is in fact an isomorphism, so that W may be viewed as a module over $\mathrm{End}_k V$. Since all $\mathrm{End}_k V$-modules are isomorphic to direct sums of copies of V, the theorem then follows.

To prove that λ is injective, we consider the involution of $k[G]$ whose restriction to G is the map $g \mapsto (\det \rho g) g^{-1}$. We show that this involution descends to an involution * of R which mimics the main involution of $\mathrm{End}_k V$ in the sense that we have $x + x^* = \mathrm{tr}\,\lambda x$ and $x x^* = \det \lambda x$ for $x \in R$. Using this involution, and the surjectivity of λ, we prove that λ is injective. For more details, *see* the "Version française abregee".

3. JACOBIANS OF MODULAR CURVES. — Let N be a positive integer. Let $X_0(N)$ be the modular curve over **Q** associated with the subgroup $\Gamma_0(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \middle| \, c \equiv 0 \pmod{N} \right\}$ of **SL** (2, **Z**). For $n \geqq 1$, let T_n denote the nth Hecke correspondence on $X_0(N)$. Abusing notation, we write again T_n for the induced endomorphism T_n^* of the Jacobian $J_0(N)$ of $X_0(N)$.

Let R be the subring of $\mathrm{End}(J_0(N))$ generated by the Hecke operators T_n with n prime to N. The theory of newforms shows that $E = R \otimes \mathbf{Q}$ is a product of totally real algebraic numbers fields E_α and that the degree $[E : \mathbf{Q}]$ is the number of (normalized) newforms of weight 2, trivial character, and level dividing N. The ring R itself is an "order" in E, it is a subring of finite index in the product $\mathcal{O} = \Pi\, \mathcal{O}_\alpha$ of the integer rings of the E_α.

Suppose that $\mathfrak{p}$ is a maximal ideal of the ring R and let $\mathbf{F} = R/\mathfrak{p}$ be its residue field. Thus **F** is a finite field, say of characteristic p. As is well known, there is a semisimple two-dimensional **F**-linear representation $\rho_\mathfrak{p}$ of $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$, characterized up to isomorphism by the following properties:

(i) The representation $\rho_{\mathfrak{p}}$ is unramified outside p and the prime numbers dividing N;

(ii) For l a prime not dividing Np, and $\varphi_l \in \mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ a Frobenius element for l, the element $\rho_{\mathfrak{p}}(\varphi_l)$ has trace $T_l \pmod{\mathfrak{p}}$ and determinant $l \pmod{\mathfrak{p}}$.

To construct $\rho_{\mathfrak{p}}$, one may note that the ring R operates faithfully on the abelian variety $A := \prod_{M \mid N} J_0(M)_{\mathrm{new}}$, where $J_0(M)_{\mathrm{new}}$ is the new subvariety of $J_0(M)$. The dimension of A is the degree $[E : \mathbf{Q}]$, and the decomposition of E into the product ΠE_α decomposes A, up to isogeny, as a product of abelian varieties with "real multiplication" by the factors E_α. In particular, the $\mathbf{Q}_p$-adic Tate module $\mathscr{V}_p$ of A is free of rank 2 over $E \otimes \mathbf{Q}_p$. Choose an extension $\mathfrak{P}$ of $\mathfrak{p}$ to $\mathcal{O}$, and let $E_{\mathfrak{P}}$ be the completion of E at $\mathfrak{P}$. The vector space $\mathscr{V}_{\mathfrak{P}} := \mathscr{V}_p \otimes_{E \otimes \mathbf{Q}_p} E_{\mathfrak{P}}$ is a two-dimensional representation of $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ over $E_{\mathfrak{P}}$, unramified outside pN, which has a property similar to (ii) above. Namely, the $E_{\mathfrak{P}}$-linear trace (resp. determinant) of φ_l acting on $\mathscr{V}_{\mathfrak{P}}$ is T_l (resp. l), for l prime to Np. This follows from the Eichler-Shimura relation for T_l ([7], 7.5.1), together with the invariance of T_l under the Rosati involution on $\mathrm{End}(J_0(N))$. (For more details on this latter point, *see* for example [7], Chapter 7.)

By "reducing" this representation mod $\mathfrak{P}$, one obtains a semisimple representation $\rho_{\mathfrak{P}}$ of $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ over $\mathcal{O}/\mathfrak{P}$ with properties analogous to (i) and (ii). More precisely, choose a model for the representation $\mathscr{V}_{\mathfrak{P}}$ over the completion of $\mathcal{O}$ at $\mathfrak{P}$, reduce mod $\mathfrak{P}$, and then semisimplify. The Brauer-Nesbitt Theorem implies that the resulting object does not depend on the model chosen (*cf.* [6], § 3.6). Since the traces and determinants of $\rho_{\mathfrak{P}}$ are elements of the subfield $\mathbf{F}$ of $\mathcal{O}/\mathfrak{P}$, and since the Brauer group of a finite field is trivial, $\rho_{\mathfrak{P}}$ has a model over $\mathbf{F}$ (*cf.* [1], Lemme 6.13). This is the desired representation $\rho_{\mathfrak{p}}$.

The Brauer-Nesbitt Theorem and the Čebotarev Density Theorem imply that $\rho_{\mathfrak{p}}$ is unique up to isomorphism.

Suppose now that $\mathbf{T}$ is the commutative subring of $\mathrm{End}(J_0(N))$ generated by all T_n with $n \geqq 1$. We have $\mathbf{T} \supseteqq R$. Let $\mathfrak{m}$ be a maximal ideal of $\mathbf{T}$, let k be the residue field of $\mathfrak{m}$, and let p be the characteristic of k. Let $\mathfrak{p} = R \cap \mathfrak{m}$. Then the representation $\rho_{\mathfrak{m}} := \rho_{\mathfrak{p}} \otimes_{\mathbf{F}} k$ is a semisimple two-dimensional representation of $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ over k with properties analogous to (i) and (ii). Our aim is to compare $\rho_{\mathfrak{m}}$ with the "kernel" of $\mathfrak{m}$ on $J = J_0(N)$, *i.e.*, the group $J[\mathfrak{m}] := \{ x \in J_0(N)(\bar{\mathbf{Q}}) \mid \mu x = 0 \text{ for all } \mu \in \mathfrak{m} \}$ of p-division points on J. The Eichler-Shimura relation for J shows that each Frobenius element φ_l (with l prime to Np) is annihilated by the polynomial $X^2 - T_l X + l$ on W, *i.e.*, by the characteristic polynomial of φ_l in the representation $\rho_{\mathfrak{p}}$. Accordingly, by Theorem 1, we have

THEOREM 2. — *Suppose that* $\rho_{\mathfrak{m}}$ *is an absolutely irreducible representation of* $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ *over* $\mathbf{T}/\mathfrak{m}$. *Then the representation* $J[\mathfrak{m}]$ *is isomorphic to a direct sum of copies of* $\rho_{\mathfrak{m}}$.

Remarks. — 1. Theorem 2 strengthens a result of B. Mazur ([2], p. 115) to the effect that the *semisimplification* of $J[\mathfrak{m}]$ is a direct sum of copies of $\rho_{\mathfrak{m}}$, when the latter representation is irreducible. It is to be noted in this connection that if $\rho_{\mathfrak{m}}$ is irreducible and p is odd, then $\rho_{\mathfrak{m}}$ is absolutely irreducible. Indeed, this implication follows from the fact that the image under $\rho_{\mathfrak{m}}$ of a complex conjugation in $\mathrm{Gal}(\bar{\mathbf{Q}}/\mathbf{Q})$ has the $\mathbf{F}_p$-rational eigenvalues $+1$ and -1, which are distinct if p is odd.

2. Under an assortment of mild hypotheses, $J[\mathfrak{m}]$ is in fact of dimension two ([2], [4], [3]). Whenever this is so, Mazur's result shows that $J[\mathfrak{m}]$ and $\rho_{\mathfrak{m}}$ are isomorphic,

provided that the latter representation is simple. Hence Theorem 2 gives no new information in such cases. When we replace J by the Jacobian of a modular curve other than $X_0(N)$, however, we find a larger class of instances where Theorem 2 gives new information. For example, Theorem 2 generalizes immediately to the situation where $\Gamma_0(N)$ is replaced by its analogue in the group of norm-1 elements in a maximal order in an indefinite rational quaternion algebra of discriminant prime to N. The case where $N=1$ and where the quaternion algebra ramifies at exactly two primes is discussed in [5] and alluded to in Section 1 above. As we mentioned in Section 1, [5] exhibits a class of maximal ideals $\mathfrak{m}$ for which $\rho_{\mathfrak{m}}$ is absolutely irreducible, but where $J[\mathfrak{m}]$ has dimension 4 over $\mathbf{T}/\mathfrak{m}$. The result of Mazur cited in Remark 1 implies in those cases that $J[\mathfrak{m}]$ can be written, up to isomorphism, as an extension of $\rho_{\mathfrak{m}}$ by $\rho_{\mathfrak{m}}$. The analogue of Theorem 2 implies that the extension is in fact *trivial.*

Similarly, a variant of Theorem 2 holds in the case where $X_0(N)$ is replaced by the modular curve $X_1(N)$.

4. $\mathfrak{P}$-ADIC REPRESENTATIONS. — The discussion of Section 3 suggests abstracting some of its arguments to the following situation.

Let $\mathscr{V}$ be a two-dimensional continuous representation over a finite extension E of $\mathbf{Q}_p$ of a compact group G. Let $\mathcal{O}$ be the "integer ring" of E, and let $\mathfrak{P}$ be the maximal ideal of $\mathcal{O}$. Then there exist $\mathcal{O}$-lattices in $\mathscr{V}$ which are G-stable. This implies, for each g in G, that the characteristic polynomial $P_g(X)$ associated to the E-linear action of g on $\mathscr{V}$ has coefficients in $\mathcal{O}$. Further, if $\mathscr{L}$ is a G-stable $\mathcal{O}$-lattice in $\mathscr{V}$, the vector space $\mathscr{L}/\mathfrak{P}\mathscr{L}$ is a two-dimensional representation of G over $\mathcal{O}/\mathfrak{P}$, whose semisimplification is independent of the choice of $\mathscr{L}$. Let V′ be this semisimplification. Thus V′ is the "reduction" of $\mathscr{V}$ mod $\mathfrak{P}$, and the characteristic polynomials associated to this representation are the reductions $\bar{P}_g(X)$ of the $P_g(X)$ mod $\mathfrak{P}$.

Suppose now that $R\subseteq\mathcal{O}$ is a $\mathbf{Z}_p$-subalgebra of $\mathcal{O}$ which contains the coefficients of all polynomials $P_g(X)$, and let $\mathfrak{p}=R\cap\mathfrak{P}$. Then $R/\mathfrak{p}$ is a subfield of the finite field $\mathcal{O}/\mathfrak{P}$ which contains the coefficients of the polynomials $\bar{P}_g(X)$. Accordingly, by the argument mentioned above, V′ has a model V over $R/\mathfrak{p}$; this is a two-dimensional representation of G over $R/\mathfrak{p}$.

Finally, suppose that $\mathscr{M}$ is an R[G]-submodule of $\mathscr{V}$, and let $W=\mathscr{M}/\mathfrak{p}\mathscr{M}$. By the Cayley-Hamilton Theorem, $\mathscr{M}$ is annihilated by the operators $P_g(g)$. Therefore, W is annihilated by each $\bar{P}_g(g)$. From Theorem 1, we conclude:

THEOREM 3. — *In the situation described above, suppose that* V *is absolutely irreducible. Then* W *is a direct sum of copies of* V.

5. COMPLEMENTS. — Theorem 1 becomes false if three-dimensional representations are considered instead of two-dimensional representations. To see this, we note that the alternating group A_4 of order 12 has, over any field k of characteristic different from 2, exactly one absolutely irreducible three-dimensional representation $\rho: G\to \mathrm{Aut}_k V$, up to isomorphism. The characteristic polynomials of the elements of order 1, 2, 3 of A_4 in this representation are $(X-1)^3$, $(X^2-1)(X+1)$, X^3-1, respectively. Therefore *any* k[G]-module W satisfies the hypothesis of the theorem, but not every W is isomorphic to a direct sum of copies of V.

Furthermore, Professor R. Solomon has pointed out to us that Theorem 1 becomes false if one allows the dimension of V to be arbitrary, but requires the semisimplification of W to be isomorphic to a sum of copies of V. Indeed, let $G=\mathbf{PSL}(2, \mathbf{F}_{11})$ and let H be a subgroup of G of index 11 in G Consider the permutation representation of G on G/H over the field $k=\mathbf{F}_2$, and let V be the trace-zero subrepresentation of this permutation representation Thus V has dimension 10 over k

The representation V is the unique irreducible in a 2-block of defect 1 for G This means that the principal indecomposable module for this block is a *nonsplit* extension W of V by itself However, W satisfies the annihilation hypothesis of Theorem 1 relative to the characteristic polynomials of V Indeed, let g be an element of G, and let n be the order of g If n is odd, W splits as a $k[\langle g \rangle]$-module by Maschke's theorem If n is even (*i e*, $n=2$ or 6), a direct check shows that X^n-1 divides the characteristic polynomial of g on V

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